U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-264 428

National Plan for the Safety and Health of Divers in Their Quest for Subsea Energy

Undersea Medical Society, Inc, Bethesda, Md

Prepared for

Public Health Service, Rockville, Md

Jan 77

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/7-77-028

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
National Plan for the Safety and Health of Divers in their Quest for Subsea Energy.

5. REPORT DATE
January 1977 issuing date

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Charles W. Shilling, M.D. principle investigator
Marthew Beckett, Editor Undersea Medical Society, Inc.

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Undersea Medical Society Inc.
9650 Rockville Pike
Bethesda, Maryland 20014

10. PROGRAM ELEMENT NO.
EHE-625

11. CONTRACT/GRANT NO.
210-75-0078

12. SPONSORING AGENCY NAME AND ADDRESS
Office of Energy, Minerals & Industry
Office of Research & Development
U.S. Environmental Protection Agency
Washington, DC 20460

13. TYPE OF REPORT AND PERIOD COVERED
Final

14. SPONSORING AGENCY CODE
EPA/600/17

15. SUPPLEMENTARY NOTES
NIOSH, ERDA, NOAA, and NIH (Other Sponsoring Agencies)

16. ABSTRACT

The report contains

→ Recommendations for improving the health and safety of divers are contained in fourteen biomedical topical chapters. They are: 1. Exbhange of Inert Gases, Oxygen and Carbon Dioxide; 2. Osteonecrosis; 3. Compression and Decompression Protocols; 4. Respiratory/Pulmonary Function in Hyperbaric Exposures; 5. Audio/Vestibular Derongements; 6. High Pressure Nervous Syndrome; 7. Thermal Problems; 8. Use ofDrugs and other Medical Treatment under Hyperbaric Conditions; 9. Physiological and Toxic Effects of Respiratory and Contaminant Gases (Acute and Chronic); 10. Cognitive and Psychomotor Performance; 11. Oxygen; 12. Assessment of Gases suitable for Diving; 13. Microbiological Aspects; and 14. Subtle Physiology Changes.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Ecology Environments	Energy Oil/Gas	06 I,K,J

18. DISTRIBUTION STATEMENT
Release Unlimited

19. SECURITY CLASS (This Report)
U.C.

20. SECURITY CLASS (This page)
U.C.

21. NO. OF PAGES
521

22. PRICE

EPA Form 2220-1 (9-73)

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

SUBJECT: Report(s) for Inclusion in NTIS

DATE: March 11, 1977

FROM: Gilbert M. Gigliotti G.M.G./cak
Director, Technical Information Staff

mdf

TO: Input Branch
National Technical Information Service
U.S. Department of Commerce
Springfield, Virginia 22161

Enclosed are reports for inclusion in the National Technical Information Service. All required information and forms are included.

If you have any questions or need any other information please call Mrs. Cynthya Holley (513/684-7555). Thank you for your cooperation.

TITLE (Report Number)	COPIES
National Plan for the Safety and Health of Divers in Their Quest for Subsea Energy	1

EPA-600/7-77-028

cc: Richard Laska
Vivian Morgan

This is the only copy of enclosed publication. Please send us a copy when you print this manual.

IAG-76-1

EPA-600/7-77-028
January 1977

PB 264 428

NATIONAL PLAN FOR THE SAFETY AND HEALTH OF DIVERS IN THEIR QUEST FOR SUBSEA ENERGY

Work Performed Under Contract #210-76-0078

with the

NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL HEART AND LUNG INSTITUTE – NIH

and additional support from the

ENVIRONMENTAL PROTECTION AGENCY

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA-600/7-77-028
January 1977

NATIONAL PLAN FOR THE SAFETY AND HEALTH OF DIVERS IN THEIR QUEST FOR SUBSEA ENERGY

Principal Investigator: Charles W. Shilling, M.D.
Editor: Marthe W. Beckett

Work conducted by:

Undersea Medical Society, Inc.
9650 Rockville Pike
Bethesda, Maryland 20014

Reproduction in whole or in part is permitted for any purpose of the U.S. Government.

The opinions, conclusions and recommendations contained in this report are not to be construed as official or necessarily reflecting the views of the supporting Federal agencies.

ia

TABLE OF CONTENTS

Foreword xix
Introduction xx

Report *pages*

Audio/Vestibular Derangements .... 1-i *to* 1-23
Osteonecrosis .... 2-i *to* 2-17
Subtle Physiological Changes .... 3-i *to* 3-25
Respiratory/Pulmonary Function in Hyperbaric Exposures .... 4-i *to* 4B-1
Psychological Factors Involved in Undersea Hyperbaric Exposures (Retitled – Selection and Training of Professional Divers) .... 5-i *to* 5-43
Cognitive and Psychomotor Performance .... 6-i *to* 6-22
Exchange of Inert Gases, Oxygen and Carbon Dioxide .... 7-i *to* 7-10
Use of Inert Gases Other Than Nitrogen and Helium (Retitled – Assessment of Gases Suitable for Diving) .... 8-i *to* 8-17
Physiological and Toxic Effects of Respiratory and Contaminant Gases (Acute and Chronic) .... 9-i *to* 9-33
Oxygen .... 10-i *to* 10-14
Use of Drugs and Other Medical Treatment Under Hyperbaric Conditions .... 11-i *to* 11-20
High Pressure Nervous Syndrome .... 12-i *to* 12-88
Microbiological Aspects .... 13-i *to* 13-16
Thermal Problems .... 14-i *to* 14-10
Compression and Decompression Protocols .... 2T-i *to* 2T-13
Systems Design Criteria .... 3T-i *to* 3T-7
Monitoring Techniques .... 4T-i *to* 4T-14
Medical and Paramedical (Retitled – Selection and Training of Physicians and Paramedics for Offshore Diving) .... 5T-i *to* 5T-8
Legal and Compensatory Aspects .... 6T-i *to* 6T-13

REPRESENTATIVES OF SUPPORTING AGENCIES

NIOSH	Dr. Alan Purdy
ERDA	Dr. Walter Weyzen
NHLI - NIH	Dr. Claude Lenfant
NOAA	Dr. James Miller Dr. Donald Beaumariage

UNDERSEA MEDICAL SOCIETY, INC.
NATIONAL PLAN STAFF

Project Manager	Nancy Riegle
Editor	Marthe Beckett
Office Staff	Melinda Brady Claire Randlett Carla Walsh
Bibliographer Assistants	Mrs. Margaret Werts Mrs. Rosemary Mathias
Administrative Assistant	Mrs. Catherine Coppola
Executive Secretary Assistant	Dr. Charles Shilling Mrs. Yvette Desautels

Preceding page blank

NATIONAL PLAN COMMITTEES

#1 **AUDIO/VESTIBULAR DERANGEMENTS**
Dr. Joseph Farmer (Chairman)

LCDR Robert A. Kennedy, MC, USN
Dr. James G. McCormick
Dr. Kenneth Money

#2 **OSTEONECROSIS**
Dr. Kent Smith (Chairman)

Dr. John Heard
Dr. Lent Johnson
Dr. John Paul Jones
Dr. J. Leon Sealey
Dr. Dennis N. Walder

#3 **SUBTLE PHYSIOLOGICAL CHANGES**
Dr. Lutz A. Kiesow (Chairman)

Dr. Ralph Brauer
Dr. Victor Frattali
Dr. Richard B. Philp

#4 **RESPIRATORY/PULMONARY FUNCTION IN HYPERBARIC EXPOSURES**
Dr. Herbert Saltzman (Chairman)

Dr. Leon Farhi
CDR W. H. Spaur, MC, USN
Dr. Lawrence Wood

#5 **PSYCHOLOGICAL FACTORS INVOLVED IN UNDERSEA HYPERBARIC EXPOSURES**
Dr. Arthur Bachrach and Dr. James Miller (Chairmen)

Dr. Harold Ginzburg (Advisor)
Mr. James T. Joiner
Mr. Ramsey Parks
Mr. James Stewart

#6 **COGNITIVE AND PSYCHOMOTOR PERFORMANCE**
Dr. Glen Egstrom (Chairman)

Dr. Arthur Bachrach
Dr. Dorothy Fletcher
Dr. W. S. Vaughan

#7 **EXCHANGE OF INERT GASES, OXYGEN, AND CARBON DIOXIDE**
Dr. Brian Hills (Chairman)

Dr. Kenneth Ackles
Dr. H. V. Hempleman
Mr. Alan Krasberg

#8 USE OF GASES OTHER THAN NITROGEN AND HELIUM
Dr. Robert Hamilton (Chairman)

Dr. Ralph Brauer
Mr. Peter Edel
Mr. Robert Gilardi

#9 PHYSIOLOGICAL AND TOXIC EFFECTS OF RESPIRATORY AND CONTAMINANT GASES (ACUTE AND CHRONIC)
Dr. Karl Schaefer (Chairman)

LT Melvin Andersen, MC, USN
Dr. Peter Bennett
Dr. Robert Hamilton
Mr. Charles Hedgepeth

#10 OXYGEN
Dr. James Clark (Chairman)

Dr. William Currie
Dr. Morris Faiman
Dr. Aron Fisher
Dr. Aaron Sanders
Dr. Donald Tierney

#11 USE OF DRUGS AND OTHER MEDICAL TREATMENT UNDER HYPERBARIC CONDITIONS
CAPT Tor Richter, MC, USN (Chairman)

Dr. Colin Jones
Dr. Tor Nome
Dr. David Youngblood

#12 HIGH PRESSURE NERVOUS SYNDROME
Dr. Peter Bennett (Chairman)

Dr. Arthur Bachrach
Dr. Ralph Brauer
CAPT Lawrence Raymond, MC, USN (Advisor)
Dr. Jean-Claude Rostain

#13 MICROBIOLOGICAL ASPECTS
LCDR Andre Cobet, MSC, USN (Chairman)

CAPT M. Mazzarella, DC, USN
Dr. E. V. Orsi
CAPT Norbert Schlamm, MSC, USN

#14 THERMAL PROBLEMS
Dr. Paul Webb (Chairman)

Mr. Wallace Jenkins
Mr. Charles Johnson
Mr. Dick Long
CAPT Lawrence Raymond, MC, USN
Mr. Gene Smith

Training, Technological and Administrative Committees

#1T OPERATING STANDARDS – Cancelled

#2T COMPRESSION AND DECOMPRESSION PROTOCOLS
Dr. Robert Hamilton (Chairman)

Dr. E. E. P. Barnard, Surg. Capt., RN
Dr. Peter Bennett
Mr. C. H. Hedgepeth (Advisor)
Dr. H. V. Hempleman
Dr. Brian Hills
Dr. Russell Peterson
Dr. Kent Smith

#3T SYSTEMS DESIGN CRITERIA
Mr. Bruce Gilman (Chairman)

Mr. Anthony Gaudiano
Mr. William Gianotti
CAPT Paul Linaweaver, Jr., MC, USN

#4T MONITORING TECHNIQUES
Mr. Andre Galerne (Chairman)

Dr. Kenneth Ackles
Mr. Charles Duff
LCDR David Hall, MSC, USN
Mr. L. S. Linderoth
Dr. M. Spencer

#5T MEDICAL AND PARAMEDICAL
Dr. Eric Kindwall (Chairman)

Dr. Harold Ginzburg
Mr. Chester A. Langworthy
Mr. Joseph Rood, Jr.
Dr. David Youngblood

#6T LEGAL & COMPENSATORY ASPECTS
Dr. Peter Bennett (Chairman)

Mr. L. J. Christoffersen
Mr. Ray Curtis
Mr. James Dawson
Mr. John Harter
Mr. Harold Lamy
Mr. Nolan Prejeant
Mr. Stanley Rauhut
Mr. Paul Woodhall

CHAIRMEN OF THE NATIONAL PLAN COMMITTEES

Arthur Bachrach, Ph.D.
Chairman, Behavioral Sciences Department
Naval Medical Research Institute

Peter B. Bennett, Ph.D.
Co-Director, F. G. Hall Environmental Research Laboratory
Duke University Medical Center

James M. Clark, M.D., Ph.D.
Assistant Director, Institute for Environmental Medicine
University of Pennsylvania

Andre Cobet, LCDR, MSC, USN
Executive Officer
Naval Biomedical Research Laboratory

Glen Egstrom, Ph.D.
Director, Underwater Kinesiology Laboratory
University of California

Joseph C. Farmer, Jr., M.D.
Division of Otolaryngology
Duke University Medical Center

Andre Galerne
President, International Underwater Contractors, Inc.

Bruce A. Gilman
Executive Vice President, Perry Oceanographics, Inc.

Robert W. Hamilton, Jr., Ph.D.
Tarrytown Labs, Ltd.

Brian A. Hills, Ph.D.
Chief, Hyperbaric Physiology Section
University of Texas Medical Center

Lutz A. Kiesow, M.D.
Director, Experimental Medicine
Naval Medical Research Institute

Eric Kindwall, M.D.
Director, Department of Hyperbaric Medicine
St. Lukes Hospital, Milwaukee

Tor Richter, CAPT, MC, USN
    Commanding Officer, Naval Regional Medical Center
    Camp Lejeune, North Carolina

Herbert A. Saltzman, M.D.
    Director, F. G. Hall Environmental Research Laboratory
    Duke University Medical Center

Karl E. Schaefer, M.D.
    Chief, Biomedical Sciences Division
    Naval Submarine Medical Research Laboratory

Kent H. Smith, D.V.M., Ph.D.
    Director, Hyperbaric Research
    Virginia Mason Research Center

Paul Webb, M.D.
    Webb Associates
    Yellow Springs, Ohio

MEMBERS OF THE NATIONAL PLAN COMMITTEES

Kenneth Ackles, M.D.
Head, Pressure Physiology Group
Defense and Civil Institute of Environmental Medicine

Melvin Andersen, LT, MC, USN
Chief, Biomedical Sciences Division
Naval Submarine Medical Research Laboratory

Arthur Bachrach, Ph.D.
Chairman, Behavioral Sciences Department
Naval Medical Research Institute

E. E. P. Barnard, M.D., Ph.D.
Department of Medical Director General (Navy)
Ministry of Defense, London

Peter Bennett, Ph.D.
Co-Director, F. G. Hall Environmental Research Laboratory
Duke University Medical Center

Ralph Brauer, M.D.
Institute of Marine Biomedical Research

L. J. Christoffersen
Safety Director, Taylor Diving and Salvage Company, Inc.

William Currie, Ph.D.
Division of Radiobiology
Duke University Medical Center

H. Ray Curtis
Manager, Ocean Systems, Inc.

James Dawson
Managing Director
Undersea Projects Insurance Brokers, Ltd.

Charles Duff
Manager, Medical Department
Taylor Diving and Salvage Company, Inc.

Peter Edel
Sea-Space Research

Morris Faiman, Ph.D.
School of Pharmacy
University of Kansas

Leon Farhi, M.D.
Department of Physiology
State University of New York at Buffalo

Aron Fisher, M.D.
School of Medicine
University of Pennsylvania

Dorothy Fletcher, Ph.D.
Institute for Environmental Medicine
University of Pennsylvania

Victor Frattali, Ph.D.
Environmental Biosciences Department
Naval Medical Research Institute

Anthony Gaudiano
Vice President, Engineering
Taylor Diving and Salvage Company, Inc.

William Gianotti
Operations Coordinator
Ocean Systems, Inc.

Robert Gilardi
AIRCO Industrial Gases

Harold Ginzburg, M.D.
Medical Director
Tarrytown Labs, Ltd.

David Hall, LCDR, MSC, USN
U.S. Navy Submarine Development Group One

Robert W. Hamilton, Jr., Ph.D.
Tarrytown Labs, Ltd.

John Harter, P.E.
President, Harter Underwater Corporation

John Heard, M.D.
New Orleans, Louisiana

Charles Hedgepeth
    Operations Manager
    Ocean Systems, Inc.

H. V. Hempleman, Ph.D.
    Superintendent
    Royal Naval Physiological Laboratory

Brian Hills, Ph.D.
    Marine Biomedical Institute
    University of Texas Medical Center

Charles Johnson
    Duke University Medical Center

Lent Johnson, M.D.
    Armed Forces Institute of Pathology

James Joiner
    Executive Director, Commercial Diving Center

Colin Jones, M.D.
    Medical Advisor
    B. P. Petroleum Development Ltd.

John Paul Jones, Jr., M.D.
    Medical and Research Director
    Diagnostic Osteonecrosis Center and Research Foundation

Robert Kennedy, CDR, MSC, USN
    Head, Human Factors Engineering Branch
    Pacific Missile Test Center

Alan Krasberg
    Director of Research and Development
    K. D. Marine Overseas, Ltd.

Harold Lamy, Attorney
    New Orleans, Louisiana

Chester Langworthy
    Environmental Biosciences Department
    Naval Medical Research Institute

Paul Linaweaver, Jr., CAPT, MC, USN
    Submarine Development Group One

L. Sigfred Linderoth, Jr.
Technical Director, F. G. Hall Environmental Research Laboratory
Duke University Medical Center

Richard Long
President, Diving Unlimited International

James McCormick, Ph.D.
Bowman-Gray School of Medicine
Wake Forest University

M. Mazzarella, CAPT, DC, USN
Naval Submarine Medical Research Laboratory
Naval Submarine Base

Kenneth Money, M.D.
Director, Biosciences Division
Defense and Civil Institute for Environmental Medicine

Tor Nome, M.D.
Hospital of Ragland, Norway

Ernest Orsi, Ph.D.
Department of Biology
Seton Hall University

Ramsey Parks
Chairman, Marine Technology Department
Santa Barbara City College

Russell Petersen, Ph.D.
Institute for Environmental Medicine
University of Pennsylvania

Richard Philp, Ph.D.
Department of Pharmacology
University of Western Ontario

Nolan Prejeant
Highland Insurance Company
New Orleans, Louisiana

Stanley Rauhut, Attorney
Houston, Texas

Lawrence Raymond, CAPT, MC, USN
Head, Pulmonary Branch
Naval Medical Research Institute

Joseph Rood, Jr.
Maryland Fire and Rescue Institute
University of Maryland

Jean-Claude Rostain, Ph.D.
Laboratoire de Neurophysiologie Applique
Marseille, France

Aaron Sanders, Ph.D.
Division of Radiobiology
Duke University Medical Center

Norbert Schlamm, CAPT, MSC, USN
Naval Medical Research and Development Command
National Naval Medical Center

J. Leon Sealey, M.D.
Northwest Industrial Medical Clinic, Inc.

Kent Smith, D.V.M., Ph.D.
Director Hyperbaric Research
Virginia Mason Research Center

N. Eugene Smith
Engineering Manager
Sub-Sea International

William Spaur, CAPT, MC, USN
Senior Medical Officer
Navy Experimental Diving Unit

Merrill Spencer, M.D.
Director, Administration and Clinical Research Center
Institute of Applied Physiology and Medicine

James Stewart
Diving Officer, Scripps Institution of Oceanography

Donald Tierney, M.D.
Division of Pulmonary Disease
University of California

William Vaughan, Jr., Ph.D.
President, Oceanautics, Inc.

Dennis Walder, M.D.
Department of Surgery
University of Newcastle Upon Tyne

xv

Lawrence Wood, M.D.
Health Sciences Center, Winnepeg

Paul Woodhall
President, Professional Divers Local #1012
United Brotherhood of Carpenters and Joiners

David Youngblood, M.D.
Medical Director
Oceaneering International, Inc.

"The more we study, the more we discover our ignorance."

Shelley

When we began this contract, we had great expectations of producing a document which would encompass all of the problems encountered in present-day diving. As we proceeded, it became apparent that there were many difficulties which we had not foreseen. In a field which is expanding and changing as rapidly as deep-sea diving, no plan, however comprehensive, can ever be definitive; if the National Plan has increased our understanding of diving and laid the basis for more research, it will have served its purpose.

Alan Purdy, Ph.D.,
Project Officer, NIOSH

Walter Weyzen, M.D., Ph.D.,
Project Monitor, ERDA

Claude Lenfant, M.D.,
Project Monitor, NHLI

James Miller, Ph.D.,
Donald Beaumariage, D.Sc.,
Project Monitors, NOAA

FOREWORD

The energy crisis confronting our nation requires the development of the oil and gas deposits located on the continental shelves beneath the sea. These new deposits are generally located in deep, rough, and cold waters.

The deep-sea diver is a key element in obtaining this energy. Though some undersea operations are automated, most are not, and they therefore require the presence of divers.

The divers themselves are tough, intelligent, and usually well trained. They are supported by advanced technology which has been developed by the industrial and scientific sectors, as well as the government. Nonetheless, the necessity for more divers to work in harsher environments in less time than ever before called for a re-evaluation of the situation.

The agencies sponsoring the National Plan (ERDA, NHLI, NIOSH, and NOAA) found that the many excellent research projects related to commercial diving were insufficiently coordinated. We also felt that there was a need to know the state of the art in both operations and research, and what research ought to be done to face the tasks before us. This, then, was the reason for this contract.

As Project Officer, I have reviewed the nineteen monographs that make up the National Plan. They will provide a firm basis for research to improve the safety and health of divers, now and for several years to come.

The Undersea Medical Society deserves a vote of thanks for doing an outstanding job. In particular, the Principal Investigator, Dr. "Chuck" Shilling, and his staff, Marthe Beckett, Nancy Riegle, and Margaret Werts, worked far beyond the call of duty.

The members of the committees which produced the National Plan were all volunteers, who labored for many hours and days without compensation. They tackled a formidable task and produced excellent results.

Many of the participants were from the U.S. Navy. Their particular point of view and the knowledge they supplied were essential in accomplishing this task. We also thank the governments or institutions of Canada, Denmark, France, Great Britain, Norway, and Sweden, for allowing some of their leading scientists to take part.

Finally, I wish to give personal thanks to those in the government who had a direct hand in making this project a success, Dr. Donald Beaumariage and Dr. James Miller of NOAA, Dr. Claude Lenfant of NHLI, and Dr. Walter Weyzan of ERDA.

Alan H. Purdy, Ph.D.
Project Officer
National Institute for
Occupational Safety and Health

Preceding page blank

INTRODUCTION

As the United States confronted the energy crisis early in 1974, it became obvious that the nation would have to increase its exploitation of underwater resources on a vast scale.

In the search for and recovery of subsea energy, the deep-sea diver is an indispensable component. Working conditions on the continental shelf, however, are unrelentingly hostile; the health and safety of the divers who work in this environment must be protected from the hazards which increasingly threaten them.

The National Institute of Occupational Safety and Health (NIOSH), recognizing the urgency of this assignment, organized a Diving Task Force, with representatives from three government agencies, Energy Research and Development Administration (ERDA), National Heart and Lung Institute, NIH, and National Oceanic and Atmospheric Association (NOAA), and additional members from the U.S. Navy, the Association of Diving Contractors, the United Brotherhood of Carpenters and Joiners of America, and representatives from a number of universities.

One of the early reports of this Task Force presents the background of this problem very clearly:

> "While hyperbaric medical research has a history of over 100 years, the recent global energy crisis has added a note of urgency to the need for further research. Since 1954, ten million acres of sea floor have been leased for fossil fuel exploration. Plans are now underway to lease an equivalent amount of acreage in the next 1-3 years. Not only will such plans require a very large increase in the number of divers, but the depths of planned leased areas are approaching 2,000 feet. The capability to operate safely at such depths exceeds our medical knowledge, and at the same time requires the presence of divers to execute tasks which are essential to the recovery of fossil fuels and minerals located on and beneath the sea floor. Energy-related development of deep-water (super tanker) ports and offshore power plants will also require the extensive use of divers. Other nations have already recognized the need for identifying national priorities, and regulations are currently in effect in the United Kingdom, part of Australia, and Japan.
>
> It is clear that the expanding Federal sea floor leasing program obligates the Government to protect the health and safety of the divers to the same extent as workers in other occupations. Extensive discussions and communication with representatives of the major diving companies have revealed their interest in cooperating with the Federal Government in solving the problems facing the offshore diving industries.
>
> At present, there is a wide diversity in the quality of research being applied to the needs of the diving industry. Thus, some organizations in the industry are highly sophisticated, while a few are not, with respect to safety and health. This diversity, coupled with greatly increased activity associated with the energy problem, and the daily increase in average depths worked, can lead to increased morbidity and mortality."

The NIOSH Task Force recommended that first priority in the general program for divers should be the development of a National Plan for the Safety and Health of Divers; the Task Force recommended that the contract be awarded to Undersea Medical Society, Inc. (UMS), with the Marine Technology Society (MTS) as a subcontractor. The twenty topics which make up the National Plan were then selected; the monographs thus deal with the most urgent problems confronting the diving industry at the present time.

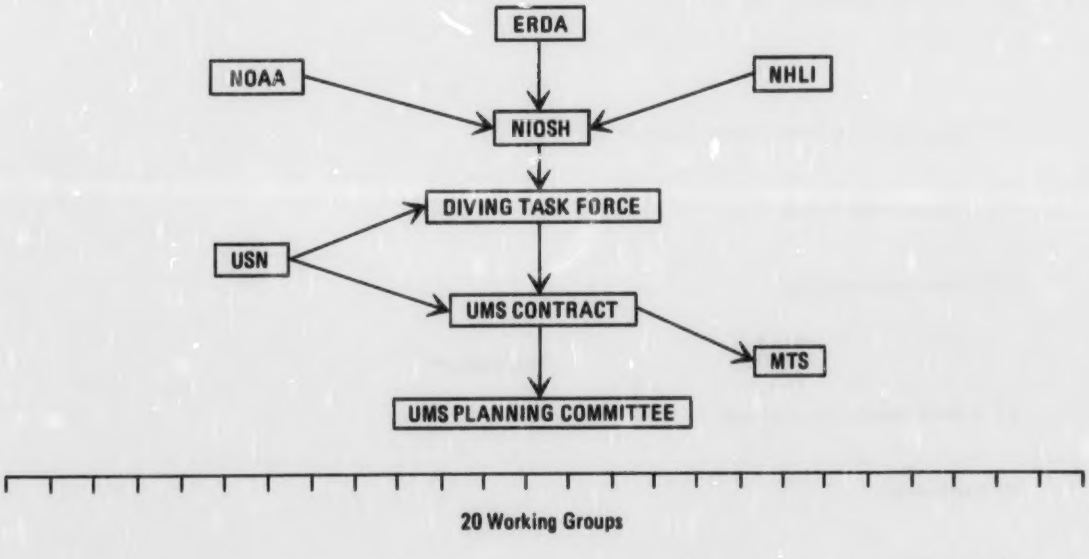
The Project Officer from the contracting agency, the National Institute for Occupational Safety and Health, was Alan H. Purdy, Ph.D., and the monitors from the other three contributing agencies were: Claude Lenfant, M.D., for the National Heart and Lung Institute; James W. Miller, Ph.D., for the National Oceanic and Atmospheric Administration; and Walter H. Weyzen, M.D., for the Energy Research and Development Administration. A series of meetings were held to discuss the problem and work out the details. The Executive Committee of the Undersea Medical Society agreed that the Society should participate.

Request for Proposals

On May 20, 1975, the Undersea Medical Society was invited to submit a proposal for a National Plan for the Safety and Health of Divers in their Quest for Subsea Energy, in accordance with the requirements of Request for Proposal No. CDC-99-OSH-165(5). In response to this request, the Society prepared a technical proposal which was submitted on June 3, 1975, and which is reproduced in its entirety (Appendix 1). The final contract to produce the National Plan was signed on June 18, 1975. The Undersea Medical Society agreed to complete the task within six months, and work was begun on July 1, 1975.

A special National Plan Advisory Committee of the Undersea Medical Society compiled a list of the six or eight leading experts in each field, and designated one from each group as chairman. The chairmen then selected the remaining members of each committee from the initial list. The accompanying outline indicates the administrative relationships in the preparation of the National Plan (Diagram #1).

Diagram 1. Agencies involved in the preparation of the National Plan.



Committee members were contacted, and a schedule of working groups established. Nancy Riegle, the project manager, handled all of the correspondence, scheduling, and coordinated the meetings of the committees. Each group met for a period of 3-5 days, during which a preliminary document was written. Mrs. Margaret Werts and her staff supplied each group with background literature and references, and the editor, Marthe Beckett, was responsible for working with the committees in the preparation of the final reports, from the preliminary stages to final copy.

From the inception to the completion of the National Plan, Mrs. Catherine Coppola handled the fiscal and administrative details, while the principal investigator, Dr. Charles W. Shilling, coordinated and directed the Society's overall effort.

The monographs of the National Plan provide a brief review of each field, an outline of the particular problems of the field as they relate to diving, and recommendations for research and development which would help to solve the most pressing problems in each field. Each committee was charged with the task of determining, for each of the subject areas:

1) what work is currently being done
2) who is doing it
3) where it is being conducted
4) what work needs to be done
5) what organizations or laboratories are capable of undertaking it
6) the order of priority for future work

National Plan Topics

The twenty topics called for in the National Plan contract are divided into four categories and listed below.*

Selection and Training

#5 Psychological Factors Involved in Undersea Hyperbaric Exposures
(Retitled – Selection and Training of Professional Divers)

#5T Medical and Paramedical
(Retitled – Selection and Training of Physicians and Paramedics for Offshore Diving)

Administrative

#6T Legal and Compensatory Aspects

Technological

#2T Compression and Decompression Protocols

#3T Systems Design Criteria

#4T Monitoring Techniques

Biomedical

#1 Audio/Vestibular Derangements

#2 Osteonecrosis

#3 Subtle Physiological Changes

#4 Respiratory/Pulmonary Function in Hyperbaric Exposures

#6 Cognitive and Psychomotor Performance

#7 Exchange of Inert Gases, Oxygen, and Carbon Dioxide

#8 Use of Gases Other Than Nitrogen and Helium
(Retitled – Assessment of Gases Suitable for Diving)

#9 Physiological and Toxic Effects of Respiratory and Contaminant Gases (Acute and Chronic)

---

*One topic called for in the original contract, Operating Standards, # 1T, does not appear in the National Plan, because NIOSH has decided in the interim to award a contract for a comprehensive study of this problem.

#10 Oxygen

#11 Use of Drugs and Other Medical Treatment Under Hyperbaric Conditions

#12 High Pressure Nervous Syndrome

#13 Microbiological Aspects

#14 Thermal Problems

General Recommendations

When the monographs of the National Plan had been completed, the chairmen of the individual committees met to make a number of general recommendations. These recommendations should be helpful to those who will be making decisions to support the procedures and research recommendations contained in the nineteen reports.

The chairmen unanimously agreed that the highest priority should be given to more careful selection and training of professional divers.* A recommendation in any of the nineteen reports which bears on the selection or training of divers involved in deep-sea diving is included in this general recommendation and should therefore receive the highest priority.

Second priority was given to the problem of medical and paramedical care for the crews and divers on oil rigs and platforms. This includes selection, training, and deployment of physicians and paramedics, the development of appropriate rescue vehicles, and the establishment of shore-based hospital treatment facilities.**

The chairmen of the committees were also unanimous in recommending the establishment of a coordinating body in the civilian sector whose functions would be similar to those of the Office of Naval Research for the Navy. Such a coordinating agency could provide a stable funding base, evaluate changing priorities, and in general unify undersea research in safety and health. It may not be necessary to establish a new agency to perform these tasks; expanding the functions of an established group, such as the National Oceanic and Atmospheric Administration, might be both feasible and efficient.

Establishing Biomedical Priorities

The chairmen of the National Plan committees were asked to rank the biomedical research topics of the Plan in order of national priority. Readers of the National Plan should keep a number of factors in mind when interpreting the list of priorities:

1) deep-sea diving is in a period of rapid change and priorities established today may not be valid tomorrow; the priorities recommended in the National Plan should therefore be reviewed by a group of experts, at least annually

2) it is important to remember that a research area which has received a relatively low priority on the following list may contain an individual research recommendation which is more urgent than a research category receiving a higher priority as a whole

---

*For detailed recommendations, see the list of priorities of Report 5 of the National Plan.

**In the interval between the writing of Report 5T and the completion of this volume, the Undersea Medical Society has sponsored a workshop entitled, "The Emergency Medical Technician/Diver". The recommendations of this workshop, available from UMS, should be considered in combination with the priorities of Report 5T.

3) although the importance of basic research cannot be overstated, the chairmen used two criteria, immediate and specific relevance to deep-sea diving and the saving of human lives, as the basis for the following priorities

4) finally, the authors of the National Plan recognize that other factors, such as economic and political considerations, must also be taken into account before decisons to support particular proposals are taken

The fourteen biomedical topics of the National Plan which are concerned with basic physiological mechanisms were ranked in the following order:

1. Exchange of Inert Gases, Oxygen and Carbon Dioxide
2. Osteonecrosis
3. Compression and Decompression Protocols
4. Respiratory/Pulmonary Function in Hyperbaric Exposures
5. Audio/Vestibular Derangements
6. High Pressure Nervous Syndrome
7. Thermal Problems
8. Effects of Drugs Under Hyperbaric Conditions Including Medical Treatment
   (Retitled – Use of Drugs and Other Medical Treatment Under Hyperbaric Conditions)
9. Physiological and Toxic Effects of Respiratory and Contaminant Gases (Acute and Chronic)
10. Cognitive and Psychomotor Performance
11. Oxygen
12. Use of Gases other than Nitrogen and Helium
    (Retitled – Assessment of Gases Suitable for Diving)
13. Microbiological Aspects
14. Subtle Physiological Changes

Readers of this volume are urged to study carefully the recommendations for improving the health and safety of divers which are contained in the following reports. Only careful evaluation and thoughtful interpretation of these recommendations can provide a sound and balanced basis for decisions affecting the future of diving in the United States.

Abbreviated Priorities for Each Topic

To facilitate the reader's task, the recommendations which appear at the end of each monograph of the National Plan have been grouped below, in outline form. Report 6T, Legal and Compensatory Aspects, does not include priorities. For a more detailed and comprehensive review of the research which needs to be done in each of the subject areas, the reader is referred to the individual monographs.

#1 AUDIO/VESTIBULAR DERANGEMENTS

I. **ANIMAL STUDIES**

  A. Areas of Investigation

    1. Effects of increased pressures and gas mixtures on auditory and vestibular functions
    2. Otologic adaptations of diving marine animals
    3. Effects of excessive noise
    4. Effects of compression and decompression schedules on otologic function
    5. Effect of inert gas switches on otologic function

  B. Techniques

    1. Behavioral auditory thresholds
    2. *In vivo* studies of labyrinthine microvasculature
    3. Histopathological studies
    4. Electrophysiological studies
    5. Middle ear impedance studies
    6. Pharmacological studies of blood-bubble interactions

II. **HUMAN STUDIES**

  A. Permanent Committee or Committees to:

    1. Establish auditory and vestibular conservation programs for divers
    2. Educate the diving community about diving otology
    3. Establish data collection banks for diving otologic injuries
    4. Establish program to study the temporal bones of deceased divers

  B. Otologic Function Tests of Divers During Dives

  C. Correlation of Middle Ear Equilibration Problems and Inner Ear Injuries in Divers With:

    1. Compression and decompression rates
    2. Variations in otologic anatomy and function
    3. Variations in nasal anatomy and function

#2 OSTEONECROSIS

I. SHORT-TERM PRIORITIES

A. Establishment of Central Registry With:

1. Regional examination centers
2. Certified interpreters
3. Mandatory participation of hyperbaric workers
4. Standardization and collection of radiographic and occupational data

    a. Development and dissemination of radiographic examination techniques
    b. Standardization of radiographic interpretation
    c. Establishment of serial radiographic examination

5. Periodic reporting of data analysis
6. Emphasis on determining predisposing factors

B. Research on Additional Detection Techniques

C. Investigation of Treatment for Potentially Reversible Lesions

1. Physical treatment methods, e.g., recompression, hypothermia
2. Pharmacological treatment, e.g., fibrinolytic, lipid-clearing agents, and hyperbaric oxygen

II. LONG-TERM PRIORITIES

A. Research to Establish the Cause of Osteonecrosis

B. Research on the Natural History of Osteonecrosis, to Aid in:

1. Determining age of lesion
2. Making accurate prognoses
3. Choice of treatment

    a. Reversible lesions
    b. Irreversible lesions

#2T COMPRESSION AND DECOMPRESSION PROTOCOLS

Choosing between basic research priorities and practical needs is difficult, for they are irrevocably interlocked. The committee feels strongly that funding of both basic and applied research must be concurrent. Though we appreciate the need for practical work which will permit safer and more effective diving now and in the immediate future, we recognize that most present decompression problems are caused by a serious lack of information. The committee unanimously urges that funding be more heavily weighted toward basic research so that progress can be based on firm foundations.

I. RESEARCH PRIORITIES

A. Physics and Physiology of Decompression and Decompression Sickness, and Investigation of Subclinical Sequelae

B. Factors Affecting Compression and Decompression

  1. Environmental
  2. Human

C. Monitoring of Physical and Physiological Parameters of Decompression and Decompression Sickness

II. PRACTICAL PRIORITIES

A. Development of Compression and Decompression Procedures

B. Training

C. Data Collection, Information Exchange, and Epidemiology

D. Diver Monitoring

E. Medical Treatment and Emergency Decompression

#3 SUBTLE PHYSIOLOGICAL CHANGES

Research priorities in the areas of subtle physiological changes in future diving operations can be divided into four major categories. The categories are ranked in order of priority, but it is often difficult to distinguish between priorities within each category.

The first category of priorities comprises three research areas, i.e., research into the reserve capacity of divers, detection and effects of occult (silent) bends, and changes in disease resistance and wound healing.

The second category deals with: research on the subcortical High Pressure Nervous Syndrome; the occurrence and effects of altered cell population dynamics; investigations of hormonal changes during hyperbaric exposure; studies of the reversibility of pathophysiological changes that may result from diving; and research on thermoregulation and temperature perception during dives.

The third category of priorities consists of investigations in the area of hyperbaric pharmacology, particularly as it relates to decompression. Other research topics which fall within this category are: efficacy and interactions of pharmacologic agents under hyperbaric conditons; changes and alterations in hematopoiesis; altered biorhythms; the possible development of laboratory criteria for diver selection; and the detection of physiological effects in divers, which should include concurrent studies of changes in basal metabolism.

The fourth and lowest category of priorities includes the investigation of the effects of sensory deprivation and isolation, changes in the palatability of food, the effects of alterations and changes in fluid and electrolyte balance in divers, and the effect of CO_2 retention. In addition, the relations between psychrometry and thermocomfort, the phenomenon of chamber layering, and the occurrence and effects of isobaric bends, and the possibility of post–HPNS depression, should be investigated.

#3T SYSTEMS DESIGN CRITERIA

A. Research on Electrocution Hazards of Underwater Electrical Equipment

B. Determination of Allowable Contaminant Levels for Compressed-Air Supply Systems

C. Establishing Standards for Personal Diving Equipment

D. Development of Self-Contained Power Supplies for Submersibles and Habitats

E. Research on the Physics and Effects of Sound Trnasmission on Hearing in Hyperbaric Conditions

F. Development of *In Situ* Gas Analysis Instrumentation

G. Development of Wire Rope Lubricants

H. Techniques and Means of Rewarming Divers Under Pressure

I. Determination of Human Factors to be Considered in Chamber and Systems Design

J. Methods for Avoiding Overlapping Frequencies in Diving

K. Hyperbaric Facilities List

#4 RESPIRATORY/PULMONARY FUNCTION IN HYPERBARIC EXPOSURES

I. PERFORMANCE IN THE WATER

A. Symposium to Summarize Accumulated Knowledge

B. Multivariable Dose-Response Matrix Studies of Underwater Breathing Apparatus, Men, Breathing Gases

C. Studies of Interactions Between Human Ventilatory Control and Environmental Variables

II. RESPONSES TO INCREASED HYDROSTATIC PRESSURE DURING EXPOSURES TO 160 ATA, IN GAS AND LIQUID-BREATHING ANIMALS

A. Control of Ventilation

B. Gas Exchange

1. Pulmonary
2. Peripheral

III. TISSUE RESPIRATION

A. Panel to Assess Accumulated Knowledge and Make Recommendations

IV. EFFECTS OF CARBON DIOXIDE

A. Tolerated Limits

B. Ventilatory Responses to Divers

V. PULMONARY MECHANICS

A. Statics

1. Pressure-thoracic gas volume curves during simulated dives
2. Thoraco-abdominal ventilatory muscle interactions

B. Dynamics

1. Homogeneity of inspired gas distribution
2. Mechanisms of apparent ventilatory adaptation after prolonged exposure to depth

VI. OXYGEN CONSUMPTION

A. Oxygen Cost of Breathing Dense Gases

B. Studies to Clarify Discrepancies About Oxygen Consumption During Exercise

VII. OTHER AREAS

A. Pulmonary Metabolism, Surface Activity and Defense Mechanisms

B. Novel Approaches to Overcome Limitations Imposed by Respiration

1. Gills
2. Liquid breathing

#4T MONITORING TECHNIQUES

A. Engineering Research to Monitor the Partial Pressure of Carbon Dioxide at the Diver

B. Development of Diver Safety Monitoring Package (DSM), Including Core and Inhalation/Exhalation Temperatures, Heart Rate, and Respiratory Rate

C. Simpler Application and Standardization of the Doppler Decompression Adequacy Technique

D. Equipment for Breath-by-Breath PO_2 and PCO_2 Analysis and Continuous, Reliable, and Instantaneous Readout of O_2 and CO_2 Inhalation and Exhalation

E. Compact and Comprehensive Physiological Data Acquisition System

#5 PSYCHOLOGICAL FACTORS INVOLVED IN UNDERSEA HYPERBARIC EXPOSURES

(Retitled – Selection and Training of Professional Divers)

A. Assessment of Manpower Needs to Aid in Establishment or Modification of Training Schools for Divers

B. Establishment of Central Record Depository and Mandatory Diving Logs for Divers

C. Research on Diver Characteristics, to Aid in Developing Selection Criteria

D. Research to Develop Diving Statistics

E. Establish Communication Between Diving Industry and Training Programs

F. Guidelines for Personnel Qualification With Specific Job Descriptions

G. Evaluation of Interactions Between Chemical Agents, e.g., Alcohol, Antihistamines, and Pressure, and Their Possible Effects on Training and Performance

H. Training of All Divers in Basic Life-Saving Techniques

#5T MEDICAL AND PARAMEDICAL

(Retitled – Selection and Training of Physicians and Paramedics for Offshore Diving)

I. **PHYSICIANS**

  A. Establishment of Appropriate Medical Agency to Act as Certifying Body for Training of Physicians

  B. Development of Curriculum for Training of Category I Physicians

  C. Development of Suitable Examinations for Diving Medicine Physicians

  D. Coordination and Implementation of Curriculum, Examinations, and Certification of Physicians by Certifying Agency

II. **PARAMEDICS***

  A. Establishment of Appropriate Medical Agency to Act as Certifying Body for Training of Paramedics

  B. Development of Curriculum and Certification for Diving Paramedics

  C. The Certifying Agency Should Coordinate and Implement the Recommendations for Diving Paramedics Contained in the Undersea Medical Society's Emergency Medical Technician/Diver Workshop.

---

*The priorities for paramedics contained in Report 5T differ from those presented here because a workshop on the selection, training, and certification of paramedics, sponsored by the Undersea Medical Society and the United Brotherhood of Carpenters and Joiners, was held on December 8-9, 1975. The priorities of Report 5T have been altered in accordance with the recommendations of this workshop.

#6 COGNITIVE AND PSYCHOMOTOR PERFORMANCE

A. Systematic Identification of Specific Work Requirements for Working Divers. Examples of these are:

    1. Task analysis of the jobs divers perform, to increase safety and effectiveness. Elements should include:

        a. Energy costs and physical working capacities
        b. Sensory requirements, e.g., hearing, vision, touch
        c. Cognitive requirements, e.g., memory, reasoning, computation
        d. Psychomotor assessment, e.g., dexterity, coordination

B. Human Engineering Studies of all Diver-Related Life-Support Systems, Work-Support Systems, and Tools

C. Stress Adaptation Studies to Determine Mechanisms for Specific Adaptation to Stressors which Limit:

    1. Sensory and perceptual capabilities, e.g., underwater vision, spatial orientation, and tactile discrimination

    2. Cognitive processes, e.g., procedure-following, memory, vigilance, problem solving

    3. Psychomotor processes, e.g., dexterity, simple and complex assembly, coordination

    4. Physical work capacity, e.g., strength, endurance, range and speed of motion, agility

D. Compensatory Programs Designed with Limiting Mechanisms in Mind. Overcoming Limitations will Result from Improving:

    1. Selection criteria and procedures

    2. Training and education

    3. Equipment design

    4. Work strategies and procedures

    5. Task restructuring

    6. Job Aids

#7 EXCHANGE OF INERT GASES, OXYGEN, AND CARBON DIOXIDE

A. Degree of Supersaturation of Tissue by Gas, if any, for Bubble Growth

B. Relative Contributions of Diffusion and Blood Perfusion in Controlling Tissue Gas Exchange

C. Elucidation of Critical Insult and Degree of Insult Needed to Provoke Symptoms of Decompression Sickness

D. Site of Insult Leading to each Form of Decompression Sickness, including Number of Tissues, their Anatomical Identity, and whether the Insult Occurs Intravascularly or Extravascularly

#8 USE OF GASES OTHER THAN NITROGEN AND HELIUM

(Retitled – Assessment of Gases Suitable for Diving)

Category I

- A. Conservation of Helium Resources
- B. Optimization of Helium Use at Sea

Category II

- A. Comparison of Decompression Properties
- B. Decompression Properties of Multigas Mixtures and Gas Sequencing
- C. Interaction of Various Gases with HPNS
- D. Effects of Various Gases on Respiratory Work

Category III

- A. Residual Gas-Related Decompression
- B. Comparison of Narcotic Potencies
- C. Thermal Properties
- D. Economic Feasibility Studies

Category IV

- A. Minor Components and Exotic Gas Additives
- B. Effects on Gas Exchange in Lungs
- C. Shipboard Handling Procedures
- D. Special Analytical and Monitoring Techniques

#9 PHYSIOLOGICAL AND TOXIC EFFECTS OF RESPIRATORY AND CONTAMINANT GASES (Acute and Chronic)

I. SHORT-TERM PRIORITIES

A. Education and Training of Diving Personnel

1. Normal and emergency environmental limits
2. Training in physiological aspects of equipment (diving apparatus, control and monitoring equipment)
3. Training in recognition of physiological warning signs

B. Evaluation, Testing, and Improvement of Equipment

1. Breathing apparatus (including rebreathers) for both chamber and submersible diving
2. Environmental control and monitoring systems
3. Reclamation apparatus for gases, including O_2 and CO_2

C. Improved Information Exchange

1. Better accident and incident analysis and reporting
2. Epidemiological studies of divers should be initiated as early as possible

D. Research to Establish Limits

1. Time intervals and recovery periods for different diving modes
2. Research on physiological warning signs
3. Interaction of physiological gases under increased pressure with each other and trace contaminants
4. Research on the use of air and N_2-O_2 diving to greater depth

II. LONG-TERM PRIORITIES

A. Long-term Effects of Extended Exposure to Increased O_2, CO_2, NO_2, and Trace Contaminants

#10 PHYSIOLOGIC AND TOXIC EFFECTS OF OXYGEN

Priorities within the five recommended areas of research cannot be set with any degree of confidence that they will be either appropriate or lasting. The areas are interrelated and information relevant to one is pertinent to all. Furthermore, a truly significant advance in one area may prove to be much more useful in diving than a less significant advance in another area. In response to a request to set priorities, the committee has ranked the following areas on the basis of immediate application to diving operations:

A. Effects of Oxygen Toxicity on Organ Systems and Functions

B. Agents and Procedures Which Modify Oxygen Toxicity

C. Optimization of Oxygen Therapy in Diving Accidents

D. Inter- and Intraindividual Differences in Sensitivity to Oxygen Toxicity

E. Basic Mechanisms of Oxygen Toxicity

#11 USE OF DRUGS AND OTHER MEDICAL TREATMENT UNDER HYPERBARIC CONDITIONS

A. Epidemiologic Study of Loss of Consciousness in Divers

B. Transfer of Patients Under Pressure

C. Effects of Tissue Damage on Decompression

D. Training Paramedical Personnel

E. Training Divers in Emergency Medical Techniques

F. Diver Monitoring and Communications

G. Microbiological Research, with Emphasis on Skin Infections

H. Effects of Drugs and Anesthetic Agents

I. Data Collection, Storage, Retrieval

J. Training of Medical Specialists

#12 HIGH PRESSURE NERVOUS SYNDROME

I. IMMEDIATE APPLIED RESEARCH NEEDS

A. Diagnosis of HPNS Stages: Taxonomy and Clinical Clarification of Signs and Symptoms

B. Vigilance, Microsleep, Sleep Disturbance, and Fatigue

C. Vestibular System Involvement

D. Visceral and Autonomic Effects

II. PRACTICAL PROBLEMS

A. Selection of Personnel

B. Compression Profiles

C. Accommodation and Adaptation

D. Temperature Effects

E. Environmental Setting: Open-Sea vs. Chamber Dives

F. Prophylaxis and Treatment

III. IMPLICATIONS OF HPNS FOR DEEP DIVING

A. Performance Decrement

B. Residual Effects of HPNS Exposures

C. Choice of Optimal Procedures

IV. BASIC MECHANISMS REQUIRING RESEARCH

A. Anatomical Sites of HPNS

B. Neurophysiological Substrates

C. Biophysical and Biochemical Mechanisms

D. Role of Neurotransmitters

E. Compression-Rate Dependence

F. Comparative Physiology: Relationships and Significance of Signs and Symptoms in Men and Animals

#13 MICROBIOLOGICAL ASPECTS

I. MICROBIAL PHYSIOLOGY

A. Hyperbaric Effects on:

1. Susceptibility of host to infectious disease agents
2. Host's immune response
3. Efficacy of chemotherapy in combatting infections
4. Infectivity, pathogenicity, and growth rates of disease agents
5. Medically significant properties of anaerobic disease agents
6. Susceptibility of host to bacterial toxins
7. Bacterial mutation, transformation, and dissociation rates
8. Physiological systems of microbial and mammalian cells
9. Potentially carcinogenic airborne toxicants, using a microbial detection system

II. HYPERBARIC OXYGEN AND VIRUS INFECTION

A. Screening of Selected Representatives of all Major Groups of Animal Viruses, using Standard and Modified Procedures for Virus Isolation in Cell Culture Systems

B. Combined Electron Microscope and Chemical Composition Study to Elucidate the Role of Membrane Integrity and its Modification by Viral Action

C. Studies of Changes in Early Stages of Viral Replication in Cell Culture Systems

D. Animal Studies

1. Antibody responses of different species to the same viral antigen
2. Effects of hyperbaric conditions on virus replication and immunization

E. Human Studies

1. Epidemiologic studies using cell culture virus isolation and serologic procedures
2. Electron microscope and immunologic assays of leukocyte cultures or biopsy specimens of divers

III. IMMUNOLOGICAL CONSIDERATIONS

A. Research on Herd-Infection, Herd-Immunity Phenomenon

1. Determination of length of isolation periods for divers
2. Determination of types of immunization for divers
3. Effects of pressure, time, relative humidity, and gas mix on enhancement of viral interferon production

4. **Effects of pressure, time, relative humidity, and gas mix on triggering of slow-acting viruses**

5. **Effects of diving conditions on mechanisms of subclinical or latent infections**

IV. AEROBIOLOGY

A. **Effects of Different Pressure, Temperature, and Gas Mixes on Survival of Airborne Microbes at Different Relative Humidities**

B. **Determination of Optimal Methods of Decontaminating Interior Atmosphere and/or Sufaces of Habitats**

C. **Identify Characteristics of Bacteria or Fungi which Account for their Predominance by the Mechanism of Selective Pressure**

D. **Role of Physical Transport in Survival and Selectivity of Organisms**

E. **Role of Carrier in Selectivity and Survival of Airborne Organisms**

F. **Role of Pressure, Temperature, Relative Humidity, and Gas Mix in Selectivity and Survival of Organisms**

#14 THERMAL PROBLEMS

A. Establish Interim Guidelines for Human Thermal Tolerance to Hyperbaric Exposure

B. Determine the Skin and Respiratory Heat Exchange of Divers to:

   1. Define safe limits for core, skin, and inspired gas temperatures;

   2. Develop and test predictive equations for heat transfer;

   3. Set thermal limits (wet/dry, depth, and time)

C. Find Better Ways to Monitor the Diver's Thermal State

D. Develop Improved Insulation

E. Develop Methods and End Points to Rewarm the Cold Diver

F. Design Self-Contained Power Sources for Divers, Bells, and Submersibles

G. Determine Thermodynamic and Physical Properties of Diving Gases

H. Develop Improved CO_2 Absorbents for Operational Temperature Range

I. Define Relationship Between Body Heat Loss, Temperature, and Performance

J. Investigate Role of Evaporative Heat Transfer in Hyperbaric Gas Environments

Conclusion

The monographs which follow have been ordered as they appeared in the original NIOSH contract; no significance attaches to their order in this volume.

The Undersea Medical Society and the staff and authors of the National Plan hope that the reports which follow will provide a firm basis for decisions which will improve the safety and health of the divers who work under the sea in the search for oil.

22 January 1976

C. W. Shilling, M.D.
Executive Secretary,
Undersea Medical Society

Editor's Note

Though the form and notation of the individual reports have been made to conform to the style of the volume as a whole, I have respected the tone and emphasis of the various committees whenever possible. The chairmen and members of the committees were gracious and unfailingly patient during the arduous job of writing and rewriting the reports. I am particularly grateful to Peter Bennett, Bill Hamilton, and Alan Purdy, whose comments, criticism, and encouragement greatly facilitated my task.

Marthe Beckett
Editor, National Plan

ERRATA

Report,	page,	paragraph	
3	14	4	read whose for those
6T	5	4	read state for state's
6T	8	1	read attests for attest
13	6	2	read RNase for RNAse
13	7	3	read hyperbaric for hyeprbaric
13	8	5	read is for are

AUDIO/VESTIBULAR DERANGEMENTS

Part #1 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Joseph C. Farmer, M.D., F.A.C.S. (Chairman)
Division of Otolaryngology
Dept. of Surgery
Duke University Medical Center
Durham, North Carolina

Robert S. Kennedy, CDR, MSC, USN
Head, Human Factors Engineering Branch
Pacific Missile Test Center, USN
Point Mugu, California

James G. McCormick, Ph.D.
Director of Research
Dept. of Otolaryngology
Bowman-Gray School of Medicine
Wake Forest University
Winston Salem, North Carolina

Kenneth Money, M.D.
Director, Biosciences Division
Defense and Civil Institute of Environmental Medicine
Ontario, Canada

TABLE OF CONTENTS and Organization for part 1

Audio-Vestibular Derangements

I. AUDITORY AND VESTIBULAR FUNCTION AND DYSFUNCTION 1

- A. Function
  - 1. Vestibular Function
  - 2. Auditory Function
- B. Dysfunction
  - 1. Transient Auditory and Vestibular Dysfunction
    - a. Barotitis media
    - b. Transient vertigo caused by caloric stimulation
    - c. Transient vertigo caused by unequal middle ear pressure equilibration (alternobaric vertigo)
    - d. Postural equilibrium disorders associated with HPNS
    - e. Dysequilibrium associated with temporomandibular joint disease
    - f. Motion sickness
    - g. Reported transient auditory-vestibular dysfunction of unknown importance
  - 2. Persistent Auditory and Vestibular Dysfunction
    - a. Injuries during compression or inner ear barotrauma
    - b. Otologic problems at stable deep depths
    - c. Otologic decompression sickness
    - d. Excessive noise exposure

II. RECOMMENDATIONS 10

- A. Animal Studies
- B. Human Studies

III. FACILITIES WITH DIVING AND OTOLOGIC RESEARCH PROGRAMS IN NORTH AMERICA 17

Auditory and vestibular dysfunction in diving have had a varying history. These disorders were often noted by 19th and early 20th century writers in descriptions of caisson disease or decompression sickness (3,4,12,22,39,40,67,68,75,76). As decompression schedules for air diving improved in the 1930s and early 1940s, reports of severe vertigo and/or hearing loss in diving decreased. With the recent advent of more frequent and deeper exposures, using different inert gases, problems of vertigo and hearing loss in divers have increased (41,62,26). Increased commercial and military interest in diving has resulted in more men diving deeper and more often than ever before, and has focused attention on the auditory and vestibular problems of diving. Man cannot perform sophisticated underwater operations if his auditory-communication and vestibular-orientation systems are malfunctioning. In addition to the emergency situation which auditory and vestibular problems create in operational diving, the diving and scientific communities are faced with the problems of losing highly trained divers due to permanent auditory and vestibular damage, and the ensuing costly medical treatment and disability.

Auditory and vestibular problems in divers have appeared in pressure chambers and open-sea dives, under various working conditions, and with exposures to various gas mixtures and depths. They have also been reported in submarines, following breath-hold dives, during compression, at stable deep depths, and during decompression. In addition, excessive noise exposure in diving chambers and helmets has been implicated in neurosensory deafness in divers. The few animal investigations which have been done confirm that auditory and vestibular damage can occur in exposure to compressed gas environments.

The purpose of this report is to recommend a classification of these problems which accords with our current state of knowledge, to list the available resources in North America, and to propose future areas of investigation which will help in solving these problems.

I. AUDITORY AND VESTIBULAR FUNCTION AND DYSFUNCTION

A. Function

1. Vestibular Function

In terrestrial environments, proper spatial orientation depends upon central nervous system integration of information from proprioceptive, visual, vestibular, and auditory stimuli. In diving, proprioceptive, visual, and auditory inputs are frequently distorted (17), and proper spatial orientation therefore becomes more dependent on input from the vestibular system.

The otolithic system conveys information about linear motion and direction of gravity. In the diving environment, confusion about the direction of up and down vectors sometimes occurs (55,56,59).

This confusion can probably be minimized by practice. The semicircular canal system provides information about angular motion. There is no reason, theoretically, why this organ complex should not function normally in the diving environment, and stabilization of the retinal image with head movements should occur in the usual way. Indeed, in an environment with decreased sensory input, the semicircular canal system may be useful also for finding one's way about, for navigation, and for maintaining spatial orientation and place memory for motor work. On the other hand, biases within the system or interactions with other physiologic systems can cause errors in interpretation of vestibular information.

2. Auditory Function

In the absence of decompression sickness or otologic barotrauma, according to present detection methods, humans have been exposed to simulated depths in chambers of up to 1000 fsw without demonstrable changes in cochlear function. Depth-related, reversible, conductive hearing losses, thought to be due to the increased impedance of the middle ear transformer in denser gas combined with changes in middle ear resonance frequency associated with helium have been noted (29,27,73,26). In wet diving with no barotrauma or decompression sickness, air conduction thresholds have been shown to undergo great increases; however, no changes have been noted in inner ear function to depths up to 105 fsw. Present concepts suggest that bone conduction is the major hearing mechanism for divers immersed in water (14,15,66,36,78,53).

Many previous studies have shown decreases in auditory-evoked responses during exposures to compressed nitrogen and helium environments (5,61,10,6). However, auditory-evoked responses are directly dependent upon stimulus intensity. None of these earlier studies corrected the stimulus intensity for the known decreases in outputs of auditory transducers and transient conductive hearing losses which occur in compressed gas environments (26).

Animal studies of auditory function during dives designed to avoid barotrauma and decompression sickness have shown mixed results. Miller has demonstrated that cats develop losses of cochlear potentials in air and helium dives up to 300 fsw. These losses recovered infrequently during decompression (51). In an unpublished study, Thomas and his co-workers noted losses of cochlear microphonics and auditory nerve action potentials in guinea pigs during shallow air diving. These losses did not recover with decompression. In these experiments, excessive chamber noise was present, and the possibility exists that cochlear damage occurred as a result of noise trauma rather than exposure to compressed air.

Investigations of guinea pigs subjected to deep helium-oxygen dives designed to prevent middle ear barotrauma and decompression sickness have shown no significant temporal bone histopathology by light microscopy. In these same animals the sensory inner ear hair cells demonstrated mild decreases in electrical function, similar to the findings seen in Miller's studies noted above (48).

There is good evidence to suggest that both monaural and binaural auditory cues can be used for underwater spatial localization, and that learning can improve these skills (38).

In undersea conditions with frequent impairment of vision, the auditory system becomes the key communication mechanism available to humans. As men are exposed to deeper depths and different gas mixtures, speech frequently becomes distorted because of changes in sound transmission. Extensive investigations have resulted in the development of instruments which satisfactorily decode the distortions of helium speech; helium speech discrimination also improves with experience.

B. Dysfunction

1. Transient Auditory and Vestibular Dysfunction

Transient auditory and vestibular dysfunction in diving can be defined as non-persistent hearing loss or vertigo which does not result in permanent injury. Transient dysfunction has been described during a variety of diving conditions. Such dysfunction has not resulted in permanent otologic injury, but it has significantly reduced diver performance and has presented serious safety hazards at depth.

a. Barotitis media

The most frequently occurring otologic problem associated with diving is aural barotrauma, resulting from a pressure differential between the middle ear and the external environment. This problem is generally noted during compression and reflects the inability to clear the ears adequately. In 1954, Weaver and Lawrence demonstrated in animal experiments that a conductive hearing loss occurs when positive or negative pressure is applied to the middle ear cavity. This effect is greater for the low frequency range of hearing (79). Other studies have suggested that barotitis media is a reversible problem and usually does not result in permanent otologic injury (35,71). Techniques currently exist which offer adequate means of preventing this trauma in most individuals selected as suitable for diving by standard selection criteria (65,35).

b. Transient vertigo caused by caloric stimulation

During certain diving conditions, transient vertigo caused by the unequal entry of cold water into the external auditory canals occurs, secondary to obstruction of one canal by cerumen, otitis externa, ear plugs, or bony exostoses. Transient vertigo can also occur in divers with pre-existing tympanic membrane perforations which allow unequal entry of cold water into the middle ear and unequal caloric stimulation of the vestibular end organs. This effect occurs particularly when a diver is oriented in a position in which the lateral semicircular canal is in a vertical plane (23).

c. Transient vertigo resulting from unequal middle ear pressure equilibration (alternobaric vertigo)

Transient vertigo related to unequal middle ear pressure equilibration has been described during ascent (43,77,72) and during descent (23). This phenomenon has been attributed to a slower decrease of middle ear pressure in one ear during ascent or to a slower increase of middle ear pressure in one ear during descent with resulting unequal vestibular end organ stimulation. Individuals who have experienced transient vertigo at depth can frequently produce vertigo and vestibular nystagmus when they are on the surface by performing the Valsalva maneuver and unequally inflating the middle ears. Many of these divers have noted asymmetrical ear clearing during ascent. The subsequent vertigo usually disappears on stopping the ascent, descending again, or shortly after a sudden hissing of air into the blocked ear occurs. Using a non-traumatic technique for observing middle ear pressure changes with simultaneous electronystagmographic recordings, Tjernstrom has shown true vestibular nystagmus with asymmetrical equilibration of middle ear pressures during ascent in shallow chamber dives (74).

The exact frequency of alternobaric vertigo in diving is not known. A recent survey (44) answered by 2,053 Swedish divers indicates that 16.7% of all divers surveyed were likely to have had alternobaric vertigo. Many of these divers (97%) indicated that the vertigo lasted from a few seconds to 10 minutes. Also, divers who had experienced vertigo had more diving experience than divers without vertigo experience, and they reported more frequent instances of ear clearing problems during diving. These middle ear pressure equilibration difficulties were usually more dominant in one ear. Thus far, only one instance of persistent inner ear injury resulting from apparent alternobaric vertigo has been reported, and that occurred during ascent from a dive in which decompression sickness was possible (23). Alternobaric vertigo in diving is best treated by prevention. Individuals should not dive if difficulty with ear clearing exists or if a Valsalva maneuver at surface produces vertigo. If ear-fullness or vertigo are noted during compression, further descent should be stopped and the diver should ascend until the ears can be cleared, even if he has to return to the surface. If such symptoms are noted during ascent, the ascent should be stopped and the diver should descend until his symptoms disappear, if gas supplies and other conditions permit (26,44).

d. Postural equilibrium associated with HPNS disorders

Numerous descriptions of the High Pressure Nervous Syndrome have noted vertigo, generalized intentional tremor, and decrements in psychomotor performance in divers who undergo rapid compression with helium at deep depths (16,19,7). The vertigo has not been adequately described in most cases; indeed, it is doubtful that in many instances the subjects experienced the true spatial rotational sensations known as vertigo. Frequently these divers have described non-specific dizziness accompanied by nausea. In most of the reported cases of HPNS, these symptoms have occurred without other otologic symptoms during the dives, which eliminates barotrauma and decompression sickness as likely factors.

Recent investigations (8) using trimix breathing gases have shown that the symptoms of HPNS can be reduced by adding nitrogen to the helium/oxygen atmospheres. Subjective improvements in dizziness and nausea as well as decreases in tremor and improvements in psychomotor performance have been noted.

Electronystagmographic studies done in several laboratories on subjects during HPNS have shown no true vestibular nystagmus and no associated abnormalities in vestibular end organ function (13,28). More specific questioning of the divers has revealed that HPNS dizziness is not true vertigo, but is better described as unsteadiness with excessive movement of the field of vision upon head turning.

Other studies including balance rail tests and statometer (standing steadiness) tests on subjects experiencing HPNS have shown dysfunctions of postural equilibrium which have been related to the effects of the accompanying generalized intentional tremor on the balance mechanism. Other studies in hyperbaric air have indicated that no changes occur in the vestibulo-ocular reflex, while increases in body sway are noted with increasing depth during dives without barotrauma or decompression sickness (13,1,2).

It has been postulated that the increase in body sway and subjective dizziness and nausea of HPNS are related to dysfunction in the central vestibular system rather then the vestibular end organs (28). More specific explanations of these problems require further investigations.

e. Dysequilibrium associated with temporomandibular joint disease

It has been suggested that unilateral temporomandibular joint dysfunction resulting from long-term mouthpiece use or mandibular malocclusion can result in asymmetrical eustachian tube function that can lead to dizziness or vertigo (21,57). However, this has not been established and is doubted by most authorities.

f. Motion sickness

Motion sickness sometimes occurs on board ship before diving. If a diver has been motion sick before diving (52), he may be nauseated or drowsy, lack motivation, or in unusual cases, he may even vomit under water. Divers who experience motion sickness on board ship should not dive until such sickness has completely subsided.

g. Reported transient auditory-vestibular dysfunction of unknown importance

Psychomotor dysfunction (past pointing) has been noted in shallow underwater conditions, and is thought to be caused by an interaction between vestibular and proprioceptive input during neutral bouyancy (80). Auditory threshold shifts when upside down have been reported in dry conditions (20). So far this has not been studied in wet conditions; the importance of this to human underwater exposure is unknown and probably not significant.

2. Persistent Auditory and Vestibular Dysfunction

In recent years, persistent and permanent cochlear and vestibular injuries in various phases of diving have occurred with increasing frequency. Analysis of these injury reports indicates that the mechanisms of injury are probably dependent on the phase of diving in which the injuries occurred. Therefore, current knowledge in this field will be described for different phases of diving.

a. Injuries during compression or inner ear barotrauma

Twelve cases of round window fistulas in divers have been described (23,58,63,24,47). In most of these cases, the dives were shallow exposures in which decompression sickness was either not possible or highly unlikely. Also, in most of these instances, difficulty with ear clearing during compression and/or signs of middle ear barotrauma existed. Symptoms associated with round window ruptures have consisted primarily of severe neurosensory hearing loss and tinnitus with or without associated vertigo and nausea.

The probable mechanisms of round window rupture in diving have been suggested by Goodhill (31,32,33). During compression or rapid ascent, inadequate middle ear pressure equilibration results in a pressure differential between the middle ear and the labyrinth. This pressure differential leads to rupture of the round window. Studies in cats by Harker et al. (31) have shown that round window ruptures can occur when cerebrospinal fluid pressure is increased by 120 mm of mercury. The increased cerebrospinal fluid pressure is transmitted to the labyrinth through the cochlear aqueduct. During the Valsalva maneuver, intracochlear pressure can rise significantly because the accompanying increase in cerebrospinal fluid pressure is transmitted through a patent cochlear aqueduct; round window ruptures can then occur.

Subsequent surgical repairs of round window ruptures have led to improvement in otologic function in most cases. Edmonds and Goodhill have suggested (23,32) that divers who suffer severe hearing loss with tinnitus and/or vertigo in dives in which decompression sickness is unlikely should be placed on bed rest. Measures should be taken to avoid straining, coughing, or other maneuvers which produce increases in cerebrospinal fluid and subsequently in intralabyrinthine pressures. If no improvement in otologic function occurs within 24-48 hours, exploratory tympanotomy should be considered.

Studies of patients with sudden neurosensory hearing loss due to non-diving-related stresses have shown a high frequency of oval window annular ligament ruptures in addition to round window ruptures (33). Thus far, oval window injuries have not been reported in divers. However, this possibility certainly exists.

The frequency of round window ruptures associated with rapid compression and decompression in shallow diving is not known. Current evidence indicates that inadequate eustachian tubal function during diving seems to be the key causative factor in this problem.

Comparative anatomical and physiological studies of diving marine mammals have shown that the round window membranes in these animals have adapted to protect them from rupture during diving. Also, these creatures have an arterio-venous plexus in the middle ear space which can fill during diving to prevent middle ear barotrauma. Without these special adaptations, man is apparently especially susceptible to middle ear barotrauma and round window fistulas in diving (49,60,50).

b. Otologic problems at stable deep depths

Inner ear problems which began at stable deep depths have been described by Sundmaker and Lambertsen (70,42). Three divers each sustained a unilateral loss of labryrinthine function during a dive which involved changing of inhaled inert gases. Each diver experienced the sudden onset of vertigo, nausea, and nystagmus shortly after changing to a mixture which included neon or nitrogen; this occurred while the divers remained at a stable pressure in a helium atmosphere.

The exact mechanisms of these injuries are not known. Two theories attempt to account for the onset of symptoms shortly after the divers began to breathe a mixture in which helium was partially replaced by another inert gas. The first theory (26,11) postulates that with the sudden addition of a second inert gas at deep depth, the rate of increase in the concentration of this dissolved second gas in the perilymph and endolymph spaces is significantly different because of the difference in the blood supply to these two areas. This results in a significant difference in osmotic pressure between these two spaces, with a subsequent flux of water into the endolymphatic space and hydrops or rupture of Reissner's membrane. The second theory involves counterdiffusion principles (34, 11). With the change from one breathing mixture to another, the diffusion of the new inert gas into body tissues or spaces with the reversed diffusion of the previous inert gas results in bubbles at various tissue interfaces such as those in the inner ear between perilymph and endolymph. This bubble formation produces displacement and/or rupture of inner ear structures, with subsequent disturbed function and injury.

Understanding the mechanism of these inner ear injuries which occur at stable deep depths in association with changes of inert gas composition will require further investigation.

c. Otologic decompression sickness

Several investigations have indicated that inner ear damage can occur during decompression sickness and that the inner ear is frequently the only organ system involved (62,18,30,41,25,26). Indeed, recent evidence suggests that the inner ear is the central nervous system structure most sensitive to damage during decompression from deep helium-oxygen diving (18).

Studies of human otologic decompression sickness have shown a direct correlation between prompt recompression treatment and lack of residual otologic deficits (25,26). This suggests that bubble formation either in the labyrinthine vasculature or in the perilymphatic or endolymphatic spaces is the causative factor in such injuries. Animal studies have suggested that blood bubble interaction and decompression sickness may lead to coagulation problems or lipid embolic phenonema which may in turn lead to permanent auditory and/or vestibular damage. Inner ear hemorrhage resulting from microcirculation blockage in the labyrinth has been suggested as the mechanism of this damage. Blockage leads to breakdown of the integrity of labyrinthine microvessels due to blood stasis, with subsequent leakage of protein into the scalae. Furthermore, studies in dived animals with decompression sickness (with or without hemorrhage) have shown that the sensory hair cells of the inner ear can malfunction electrically and degenerate (46,49,50).

The overall incidence of otologic decompression sickness is higher than the previous literature has indicated. Between 10-20% of all reported decompression accidents have involved otologic symptoms, depending on whether a conservative or liberal criterion is employed (41). Moreover, the incidence appears to be even higher in civilian decompression accidents treated by the U.S. Navy. These statistics are based on a review of diving accident records over a

30-yr period (41). With the advent of saturation diving, the frequency of such accidents appears to be increasing even further, as suggested in several studies (18,62,25).

Current research would suggest the following in regard to otologic decompression sickness:

1) Cochlear and/or vestibular symptoms appearing during dives in which decompression sickness is possible and in which middle ear barotrauma is unlikely should be considered as forms of decompression sickness and should be recompressed promptly.

2) Divers who experience such symptoms during or shortly after a switch to air breathing during decompression from a deep helium/oxygen exposure should be switched back to the pre-symptom helium/oxygen atmosphere and recompressed promptly.

3) The optimal treatment depth or depth of recompression is at present unknown. In some cases, bubble formation in the inner ear might result in structural deformation, such as breaks in membranes, and prompt relief will not occur even though an adequate recompression depth which will drive the bubbles into solution is reached. Theoretically, the best form of recompression treatment would be the depth of relief or the bottom depth, whichever is lesser. Occasionally returning to the bottom depth may be hazardous or impractical, especially in the open sea. Therefore, an arbitrary level of optimal treatment depth is suggested for these situations. This level should be at least 3 atmospheres deeper than the depth at which the symptoms began.

4) The use of other measures in the treatment of otologic decompression sickness, such as anticoagulants, low molecular weight dextran, and oxygen-enriched treatment gases, has not been adequately evaluated. If inner ear hemorrhage has occurred, anticoagulation might cause additional harm and would be contraindicated.

5) Previous studies have indicated that diazepam (64, 45,9) has specific effects upon the physiologic function of the central vestibular system, and that it is clinically useful in providing relief of symptoms during vestibular disorders. Other medications, such as antihistamine derivatives designed to provide symptom relief, and drugs which supposedly increase cochlear blood flow, have not yet been found useful in the treatment of otologic decompression sickness.

d. Excessive noise exposure

Recent investigations (69,54) have indicated that divers are frequently exposed to excessive noise levels according to current surface-applied damage risk criteria. Indeed, such investigations have shown that divers develop temporary auditory threshold shifts at such noise levels. Thus, the possibility (69) of permanent neurosensory deafness in divers exposed to excessive noise exists. At present, no studies have been done to develop appropriate damage risk criteria for excessive noise exposure in diving.

II. RECOMMENDATIONS

In the following table, most of the auditory-vestibular diving problems discussed in part I of this report are listed. Problem characterics are broken down into: safety hazards, performance decrements, cost excess, and time lost. Need for knowledge is broken down into basic research, exploratory development, advanced development, and engineering development. Recommended effort is also broken down into basic research, exploratory development, advanced development, and engineering development. Each one of the above categories is ranked on a scale from one to five, lower numbers indicating more importance or higher priority.*

The committee suggests that work on the following projects be done as soon as feasible at all depths and with all gas mixtures currently in use or planned for use in the foreseeable future. Information gained from work on these projects will enhance current knowledge about auditory, vestibular end organ, and central nervous system physiology, and will result in better methods of preventing and treating otologic dysfunction and injury in divers.

A. Animal Studies

1. Animal studies of the effects of increased pressures and different gas mixtures on middle ear and cochlear function are needed, using auditory behavioral threshold techniques both in the presence and absence of barotrauma and decompression sickness.

2. Techniques to adapt present methods of visualization of the labyrinthine microvasculature in animals are needed, to allow use of these methods during diving. Previous work has clearly indicated that changes in blood and blood flow in the labyrinth may play a significant role in the pathophysiology of labyrinthine decompression sickness. Use of these techniques during various diving conditions should add to our knowledge in this area.

3. Histopathological studies of temporal bones and central vestibular structures in animals with decompression sickness and inner ear barotrauma should be expanded. The development of a technique for histological fixation while at pressure would be of great value.

---

*For a more detailed explanation of this ranking system and category definitions see the Department of the Navy, RDT & E. Management Guide Part I: System Description, 1 July 1972, Ref. Chapter I, page 9, NAVSO P-2457 (REV. 7-72).

Table 1-1. Problems and priorities in auditory and vestibular diving research.

	Problem Characteristics				Need for Knowledge				Recommended Effort				Research Value for Medicine and Fields Other than Diving
	Safety Hazard	Performance Decrement	Overall Cost Excess	Overall Time Lost	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Basic Research	Exploratory Development	Advanced Development	Engineering Development	
(Auditory and Vestibular Function)													
Vestibular Orientation and Underwater Functioning	3	4	4	4	3	3	4	4	3	4	4	5	3
Visual Stabilization with Movement Underwater	3	3	4	4	3	4	5	5	4	4	5	5	3
Hearing Decrements at Pressure	5	5	5	5	4	5	5	5	4	5	5	5	4
(Transient Dysfunction)													
Helium Speech	2	3	3	3	3	5	5	4	4	5	5	4	5
Vertigo from Caloric Effects	2	4	4	4	4	4	5	5	3	4	5	5	4
Alternobaric Vertigo	3	3	4	4	3	4	5	5	3	4	5	5	3

Table 1-1. Problems and priorities in auditory and vestibular diving research, (Cont'd.)

	Problem Characteristics				Need for Knowledge				Recommended Effort				Research Value for Medicine and Field Other than Diving
	Safety Hazard	Performance Decrement	Overall Cost Excess	Overall Time Lost	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Basic Research	Exploratory Development	Advanced Development	Engineering Development	
	(Transient Dysfunction)												
Disorders of Equilibrium with HPNS	1	1	1	2	1	2	4	5	1	3	4	3	2
Motion Sickness	2	1	4	4	4	5	5	3	3	5	4	3	3
Barotitis Media and Middle Ear Barotrauma	3	4	5	5	4	4	5	5	4	4	5	5	3
	(Persistent Dysfunction)												
Inner Ear Barotrauma	1	1	1	1	2	1	4	4	1	2	4	5	1
Inner Ear Damage Following Gas Changes at Stable Depths	1	1	2	1	1	1	5	5	1	2	4	4	2
Otologic Decompression Sickness	1	1	1	1	1	1	5	5	1	2	4	4	1

Table 1-1. Problems and priorities in auditory and vestibular diving research. (Cont'd.)

	Problem Characteristics				Need for Knowledge				Recommended Effort				Research Value for Medicine and Fields Other than Diving
	Safety Hazard	Performance Decrement	Overall Cost Excess	Overall Time Lost	Basic Research	Exploratory Development	Advanced Development	Engineering Development	Basic Research	Exploratory Development	Advanced Development	Engineering Development	
(Persistent Dysfunction)													
Excessive Noise Exposure	3	3	2	4	1	2	2	1	1	2	2	1	3

Ratings are from 1-5; lowest numbers indicate greatest severity, most knowledge needed, most effort recommended, or greatest value, respectively, for each problem.

4. The effectiveness and type of optimal recompression therapy for otologic decompression sickness need to be investigated extensively in animals. These investigations should include evaluations of otologic function and anatomy after recompression using behavorial, electrophysiological, and histological techniques.

5. Further auditory and vestibular electrophysiological and pharmacological studies are needed in animals to investigate blood bubble interactions in the labyrinthine vasculature during decompression sickness.

6. Additional studies in animals are needed to evaluate various decompression schedules and gas exchanges in relation to the frequency of otologic decompression sickness. Proposed decompression schedules should be evaluated in animals from an otologic standpoint before any new or untried schedules are used in humans.

7. Many diving marine mammals have unusual physiological and anatomical adaptations which appear to provide protection from otologic decompression sickness or barotrauma. Examples of such adaptations which have so far been identified include the absence of clotting factor XII, the presence of potent tissue stores of heparin, methods of decreasing the gas volume of the middle ear by engorgement of vasculature, and thick, multilayered, round window membranes. Further studies of these apparent adaptations and other possible adaptations in marine mammals are needed.

8. Animal studies concerning the effects of excessive noise upon cochlear function during diving and possible interactions between excessive noise exposure and otologic decompression sickness are needed. These studies should be used to develop noise damage risk criteria for diving.

9. Animal vestibular function tests are needed, including electrophysiological investigations of peripheral and central vestibular function during deep diving and with exposure to different gas mixtures.

10. Animal studies of the labyrinthine physiological effects of countercurrent diffusion after inert gas switches at stable deep depths and during decompression are needed. These tests should include electrophysiological and histological studies.

11. Animal studies of the effects of rapid compression and decompression without decompression sickness on middle ear volume and pressure characteristics and on pressure changes in the inner ear are needed. Many of these studies could be done at shallow depths and may result in additional information about optimal compression rates, as well as appropriate criteria for optimal eustachian tube function in humans.

B. Human Studies

The following human otologic dysfunction and injury studies are recommended. We suggest that implementation of the recommendations in the first four sections be accomplished by using working groups composed of experts in auditory and vestibular physiology from both the diving and non-diving communities. We feel that these committees should be established promptly under the sponsorship of the Undersea Medical Society or an appropriate undersea biomedical organization, with financial support from various federal agencies concerned with the health and safety of divers. This committee should be permanent and ongoing. It should meet regularly to restate or revise its standards and regulations in accordance with new information. It is possible that one committee might perform work in more than one or perhaps all of the areas discussed in the following four paragraphs.

1. There is an urgent need for appropriate and adequate audiological and vestibular conservation programs for divers. These programs should include the establishment of standard testing procedures on surface and at depth, the setting up of ongoing screening and testing programs, and the establishment of effective damage prevention measures in accordance with current knowledge. Emphasis should be placed on experimental diving programs, but these conservation programs should be designed to cover both routine and experimental diving adequately.

Too little attention has been given to audiological and vestibular dysfunction in divers in the past. Industry-wide, standard conservation programs in these areas should be given high priority, and should also be established in the military services.

2. The diving community, both military and non-military, needs to be better informed about otologic function, dysfunction, and permanent injury in diving. The current U.S. Navy Diving Manual and other standard diving references need significant revisions on this topic. Such revisions should include more comprehensive and up-to-date emphasis on the physiology of the auditory and vestibular system, nasal and eustachian tube function and disease, excessive noise and its effects upon cochlear function during diving, knowledge about round window ruptures and their treatment, information on vestibular injuries occurring at stable deep depths after inert gas switches, and better descriptions of the manifestations and management of otologic decompression sickness.

Current standard diving reference manuals contain a number of specific examples of misinformation or lack of information about otologic decompression sickness. At present there is no evidence that any pharmacological agent reverses the effects of otologic decompression sickness; some agents, such as heparin or other anticoagulants, might indeed produce greater injury. The only useful pharmacological agents are diazepam and droperidol, and these are only useful for the symptomatic relief of vertigo.

Some divers who have suffered severe vertigo have been returned to diving after their symptoms have subsided, without having any specific otoneurological evaluation. It has been well established that partial or complete destruction of one vestibular end organ will cause severe and acute symptoms which gradually decrease in intensity over a period of several days to several weeks after the injury. Eventually, acute symptoms subside and such individuals are asymptomatic for their usual activities. Relief of symptoms is not usually due to recovery of the injured vestibular end organ, but results from compensation within the central nervous system. Divers injured in this manner can and do have transient periods of dysequilibrium, particularly in dark, bouyant surroundings. If such an individual continues to dive and suffers injury to the non-injured vestibular end organ, permanent disability even during non-diving conditions will probably result. This committee therefore strongly recommends that the diving community be informed of this phenomenon, and that divers who suffer symptoms of inner ear injury related to diving should have complete otoneurologic evaluations after such injuries even though the acute symptoms have subsided. Any individual who demonstrates persistent inner ear end organ injury should not engage in further diving.

3. A standard program should be established in data collection banks for the recording and assimilation of otologic dysfunction and accidents in diving and the correlation of these injuries with other human biomedical characteristics and pathology.

4. A program should be established for the collection and study of the temporal bones of deceased divers, in cooperation with the Deafness Research Foundation, which is presently sponsoring a similar program.

5. Additional studies evaluating human auditory and vestibular function during all phases of diving both with and without barotrauma and decompression sickness are needed. These studies should include auditory threshold testing at all depths, but the emphasis should be on testing at depths greater than 1000 fsw. Such studies should also be done during manifestations of the High Pressure Nervous Syndrome.

6. Additional studies are needed to try to determine which individuals are prone to develop middle ear equilibration problems and inner ear injury during diving. The occurrence of such problems should be correlated with various compression rates, human anatomical and physiological variables, and otologic and nasal variations. Such variables as the relative gas volumes of the middle ear-mastoid complex (determined by temporal bone radiography or other means), the presence of nasal pathology, or the existence of paranasal sinus

disease should be correlated with the occurrence of middle ear equilibration problems. Much of this information could be obtained by retrospective studies. If prospective studies are used to obtain this information, care should be taken to ensure that the subjects used in such research are protected from possible inner ear injuries. Dive profiles in which middle ear pressure equilibration problems are likely should be avoided. Studies in which such injuries are probable should be confined to animals.

III. FACILITIES WITH DIVING AND OTOLOGIC RESEARCH PROGRAMS IN NORTH AMERICA

Most academic otolaryngology programs and some physiology and psychology programs in North America have ongoing vestibular and auditory research efforts of various types, including basic and/or clinical research. Relatively few of these programs are integrated with hyperbaric facilities or diving research efforts. Listed below are facilities known to be currently active in both areas. This listing should not necessarily be considered complete or exclusive. It was compiled according to knowledge available to this committee at this time. As future research efforts expand and improved communication channels develop among laboratories, this list will undoubtedly grow. Many current otologic research programs could make significant contributions to this field if hyperbaric facilities, such as a small animal chamber, were added to their facilities.

Institutions with Current Otologic Diving Research Programs

1. Defense and Civil Institute of Environmental Medicine; Biosciences Division, Downsview, Ontario

   Kenneth Money

2. Institute for Environmental Medicine, University of Pennsylvania, Philadelphia, Pennsylvania

   C. J. Lambertsen

3. Section of Otolaryngology, Dept. of Surgery, Bowman Gray School of Medicine, Wake Forest University, Winston-Salem, North Carolina

   James G. McCormick

4. Division of Otolaryngology, Dept. of Surgery, University of North Carolina School of Medicine, Chapel Hill, North Carolina

   William G. Thomas

5. Division of Otolaryngology, Dept. of Surgery and F. G. Hall Laboratory for Environmental Biomedical Research, Duke University Medical Center, Durham, North Carolina

   Joseph C. Farmer

6. Dept. of Otolaryngology and Marine Biomedical Institute, University of Texas Medical Branch, Galveston, Texas

   Manning J. Correia

7. Communication Science Laboratory, University of Florida, Gainsville, Florida

   H. Hollien

8. Naval Coastal Systems Laboratory/Naval Experimental Diving Unit, Panama City, Florida

   W. H. Spaur

9. Dept. of Otolaryngology, University of Washington, Seattle, Washington

   Joseph Miller

The committee wishes to point out that the U.S. Naval Aerospace Medical Institute, Pensacola, Florida is an existing U.S. Government Navy facility with an unusual capability for vestibular research. This Institute has great potential for making significant contributions to diving vestibular research.

REFERENCES

1. Adolfson, J. A., K. Bjerver, E. Fluur, and L. Goldberg. 1970. Vestibular reaction during hyperbaric conditions. *Foervarsmedicin* 6:234-238.
2. Adolfson, J. A., L. Goldberg, and T. E. Berghage. 1972. Effects of increased ambient air pressure on standing steadiness in man. *Aerospace Med*. 43:520-524.
3. Almour, R. 1942. Industrial otology in caisson workers. *N. Y. State J. Med*. 42:779-785.
4. Alt, F., R. Heller, W. Mager, and H. von Schrotter. 1897. Pathologie der Luftdruckerkrankungen der Gehororgans. (Pathology of air pressure diseases of the auditory organs. Trans. by Mrs. A. Woke, NMRI, 1972). *Monatsschr. Ohrenheilk*. 31:229-242.
5. Bennett, P. B. 1964. The effects of high pressures of inert gases on auditory evoked potentials in cat cortex and reticular formation. *Electroencephalog. Clin. Neurophysiol*. 17:388-397.
6. Bennett, P. B., K. N. Ackles, and V. J. Cripps. 1969. Effects of hyperbaric nitrogen and oxygen on auditory evoked responses in man. *Aerospace Med*. 40:521-525.
7. Bennett, P. B., and E. J. Towse. 1971. The high pressure nervous syndrome during a simulated oxygen-helium dive to 1500 ft. *Electroencephalog. Clin. Neurophysiol*. 31:383-393.
8. Bennett, P. B., G. D. Blenkarn, J. Roby, and D. Youngblood. 1974. Suppression of the high pressure nervous syndrome in human deep dives by $He-N_2-O_2$. *Undersea Biomed. Res*. 1:221-237.
9. Bernstein, P., B. F. McCabe, and J. H. Ryu. 1974. The effect of diazepam on vestibular compensation. *Laryngoscope* 84:267-272.
10. Bevan, J. 1971. The human auditory evoked response and contingent negative variation in hyperbaric air. *Electroencephalog. Clin. Neurophysiol*. 30:198-204.
11. Blenkarn, G., C. Aquadro, B. Hills, and H. Saltzman. 1971. Urticaria following the sequential breathing of various inert gases at a constant pressure of 7 ATA: A possible manifestation of gas induced osmosis. *Aerospace Med*. 42:141-146.
12. Boot, G. W. 1913. Caisson workers' deafness. *Ann. Otol. Rhinol. Laryngol*. 22:1121-1132.
13. Braithwaite, W. R., T. E. Berghage, and J. C. Crothers. 1974. Postural equilibrium and vestibular response at 49.5 ATA. *Undersea Biomed. Res*. 1:309-323.
14. Brandt, J. F., and H. Hollien. 1967. Underwater hearing thresholds in man. *J. Acoust. Soc. Am*. 42:966-971.
15. Brandt, J. F., and H. Hollien. 1969. Underwater hearing thresholds in man as a function of water depth. *J. Acoust. Soc. Am*. 46:893-897.
16. Brauer, R. W. 1968. Seeking man's depth level. *Ocean Industry* 3:28-33.
17. Brown, J. L. 1961. Orientation to the vertical during water immersion. *U. S. Naval Med. Res. Lab. Rept. No. 355*, Groton, Connecticut.
18. Buehlmann, A., and W. Waldvogel. 1967. The treatment of decompression sickness. *Helvet. Med. Acta* 33:487-491.

19. Buehlmann, A., H. Matthys, H. Overrath, P. Bennett, P. Elliott, and S. Gray. 1970. Saturation exposures of 31 ATA in an oxygen-helium atmosphere with excursions to 36 ATA. Aerospace Med. 41:394-402.
20. Corso, J. F. 1962. Bodily position and auditory thresholds. Percept. Mot. Skills 14:499-507.
21. Costen, J. B. 1934. A syndrome of ear and sinus symptoms dependent upon disturbed function of the temporomandibular joint. Ann. Otol. Rhinol. Laryngol. 43:1-15.
22. Curnow, J. 1894. Auditory vertigo caused by working in compressed air. Lancet 2:1088-1089.
23. Edmonds, C., P. Freeman, R. Thomas, J. Toukia, and F. Blackwood. 1973. Otological Aspects of Diving. Sydney, Australia: Australian Med. Publishing Co., p. 55-96.
24. Edmonds, C., P. Freeman, and J. Tonkin. 1974. Fistula of the round window in diving. Trans. Am. Acad. Ophthalmol. 78:444-447.
25. Farmer, J. C., and W. G. Thomas. 1973. Vestibular injury during diving. Foervarsmedicin 9:396-403.
26. Farmer, J. C., and W. G. Thomas. 1975. Auditory and vestibular function in diving. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. H. Elliott. London: Bailliere Tindall.
27. Farmer, J. C., W. G. Thomas, and M. J. Preslar. 1971. Human auditory responses during hyperbaric helium-oxygen exposures. Surg. Forum 22:456-459.
28. Farmer, J. C., W. G. Thomas, R. W. Smith, and P. B. Bennett. 1974. Vestibular function during HPNS. (Abstract) Undersea Biomed. Res. 1:A-11.
29. Fluur, E., and J. Adolfson. 1966. Hearing in hyperbaric air. Aerospace Med. 57:783-785.
30. Gehring, H., and A. Buehlmann. (in press). So-called vertigo bends after oxygen-helium dives. In: Proc. 5th Symp. Underwater Physiol., edited by C. J. Lambertsen. Washington, D. C.: Fed. Am. Soc. Exp. Biol.
31. Goodhill, V. 1971. Sudden deafness and round window rupture. Laryngoscope 81:1462-1474.
32. Goodhill, V. 1972. Inner ear barotrauma. Arch. Otolaryngol. 95:588.
33. Goodhill, V., I. Harris, S. Brockman, and O. Hantz. 1973. Sudden deafness and labyrinthine window ruptures. Ann. Otol. 82:2-12.
34. Graves, D., J. Idicula, C. Lambertsen, and J. Quinn. 1973. Bubble formation in physical and biological systems: a manifestation of counter-diffusion in composite media. Science 179:582-584.
35. Haines, H. L., and J. D. Harris. 1946. Aerotitis media in submariners. Ann. Otol. Rhinol. Laryngol. 55:347-371.
36. Hamilton, P. M. 1957. Underwater hearing thresholds. J. Acoust. Soc. Am. 29:792-794.
37. Harker, L., J. Norante, and J. Ryu. 1974. Experimental rupture of the round window membrane. Trans. Am. Acad. Ophthamol. Otolaryngol. 78:448-452.
38. Harris, J. D., and R. L. Sergeant. 1970. Sensory behavior of naval personnel: Monaural/binaural minimum audible angle of auditory response. U. S. Naval Submarine Med. Center Rept. No. 607.

39. Heller, R., W. Moger, and H. von Schrotter. 1895. Vorlaufige Mittheilung ueber Caissonarbeiter. (Introductory Report on Caisson Workers. Trans. by Mrs. A. Woke, NMRI, 1972). *Wien Klin. Wochenschr*. 8:475-476.

40. Keays, F. L. 1909. Compressed air illness, with a report of 3,392 cases. Ithaca, N. Y.: Cornell Univ. Med. Coll., Dept. of Med. 2:1-55.

41. Kennedy, R. S. 1974. General history of vestibular disorders in diving. *Undersea Biomed. Res*. 1:73-81.

42. Lambertsen, C. J. (in press). Collaborative investigation of limits of human tolerance to pressurization with helium, neon, and nitrogen. In: *Proc. 5th Symp. Underwater Physiol*., edited by C. J. Lambertsen. Washington, D. C.: Fed. Am. Soc. Exp. Biol.

43. Lundgren, C. E. G. 1965. Alternobaric vertigo--a diver's hazard. *Brit. Med. J*. 2:511-513.

44. Lundgren, C., O. Tjernstrom, and H. Ornhagen. 1974. Alternobaric vertigo and hearing disturbances in connection with diving: an epidemiological study. *Undersea Biomed. Res*. 1:251-258.

45. McCabe, B. F. 1973. Central aspects of drugs for motion sickness and vertigo. *Advan. Otol.-Rhino.-Laryng*. 20:458-469.

46. McCormick, J. G. 1975. Sudden hearing loss due to diving and its prevention with heparin. *Otolaryng. Clin. N. Am*. 8:417-430.

47. McCormick, J. G., J. A. Harrill, and H. E. Miller. (in press). Round window fistula in a scuba diver. *Arch. Otolaryngol*.

48. McCormick, J. G., T. Phillbrick, W. Holland, and J. A. Harrill. 1973. Diving induced sensory-neuro deafness. *Laryngoscope* 83:1483-1501.

49. McCormick, J. G., E. G. Weaver, I. L. Holleman, and J. A. Harrill (in press). Anatomical and physiological adaptations of marine mammals for the prevention of diving induced middle ear barotrauma and round window fistulas. *J. Acoust. Soc. Am*.

50. McCormick, J. G., S. G. Weaver, J. Pollin, and S. M. Ridgway. 1970. Sound conduction in the dolphin ear. *J. Acoust. Soc. Am*. 48:1418-1428.

51. Miller, H. E. 1971. Cochlear potentials at 11 atmospheres. *Laryngoscope* 81:979-988.

52. Money, K. E. 1970. Motion sickness. *Physiol. Rev*. 50:1.

53. Montague, W. E., and J. F. Strickland. 1961. Sensitivity of the water-immersed ear to high and low level tones. *J. Acoust. Soc. Am*. 33:1976-1981.

54. Murray, T. 1970. Noise levels inside Navy diving chambers during compression and decompression. *Naval Submarine Med. Center Rept. No. 643*.

55. Nelson, J. G. 1968. Effect of water immersion and body position upon perception of the gravitational vertical. *Aerospace Med*. 39:806-811.

56. Pesch, A. J. 1968. Human factors research and simulation in the design of small submersibles. General Dynamics Electric Boat Division, Groton, Conn., May 7.

57. Pinto, O. F. 1966. Temporomandibular joint problems in underwater activities. *J. Prosth. Dent*. 16:722-784.

58. Pullen, F. W. 1972. Round window membrane rupture: A cause of sudden deafness. *Trans. Am. Acad. Ophthamol. Otolaryngol.* 76:1444-1450.

59. Radloff, R., and R. Helmreich. 1968. Marine Life. In: *Groups Under Stress*, edited by R. Radloff and R. Helmreich. New York: Appleton-Century-Crofts.

60. Ridgway, S. H., J. G. McCormick, and E. G. Weaver. 1974. Surgical approach to the dolphin's ear. *J. Exp. Zool.* 188:265-276.

61. Roger, A., P. Cabarrou, and H. Gastaul. 1955. EEG changes in humans due to changes of surrounding atmospheric pressure. *Electroencephalog. Clin. Neurophysiol.* 7:152.

62. Rubenstein, C. J., and J. K. Summitt. 1971. Vestibular derangement in decompression. In: *Proc. 4th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. New York: Academic.

63. Schuknecht, H. F., and R. R. Gacek. 1973. Surgery on only-hearing ears. *Trans. Am. Acad. Ophthamol. Otolaryngol.* 77:257-266.

64. Sekitani, T., B. F. McCabe, and J. H. Ryu. 1971. Drug effects on the medical vestibular nucleus. *Arch. Otolaryngol.* 93:581-589.

65. Shilling, C. W., and I. A. Everley, 1942. Auditory acuity in submarine personnel. Part III. *U. S. Navy Med. Bull.* 40:664-686.

66. Sivian, L. J. 1943. On hearing in water vs. hearing in air, with some experimental evidence. *Office of Scientific Research and Development Rept. No. 6.1-NDRC-838.* National Defense Res. Comm., Division 6, Section 6.1.

67. Smith, A. H. 1873. *The Effects of High Atmospheric Pressure, Including the Caisson Disease.* Brooklyn: Eagle Print, p. 1-53.

68. Snell, E. H. 1896. *Compressed Air Illness (or so-called Caisson Disease).* London: H. K. Lewis.

69. Summitt, J., and J. Reimers. 1971. Noise: a hazard to divers and hyperbaric chamber personnel. *Aerospace Med.* 42:1173-1177.

70. Sundmaker, W. 1973. Vestibular function. In: *Special Summary Program*, edited by C. J. Lambertsen, Univ. of Pennsylvania: Predictive Studies III.

71. Taylor, G. D. 1959. The otolaryngologic aspects of skin and scuba diving. *Laryngoscope* 69:809-858.

72. Terry, L., and W. L. Dennison. 1966. Vertigo amongst divers. *U. S. Navy Submarine Med. Center Special Rept. No. 66-2.*

73. Thomas, W. G., J. K. Summitt, and J. C. Farmer. 1974. Human auditory thresholds during deep saturation helium-oxygen dives. *J. Acoust. Soc. Am.* 55:810-813.

74. Tjernstrom, O. 1973. On alternobaric vertigo: experimental studies. *Foervarsmedicin* 9:410-415.

75. Vail, H. H. 1929. Traumatic conditions of the ear in workers in an atmosphere of compressed air. *Arch. Otolaryngol.* 10:113-126.

76. Van Rensselaer, H. 1891. The pathology of the caisson disease. *Trans. N. Y. State Med. Soc.*, p. 408-444.

77. Vorosmarti, J., and J. J. Bradley. 1970. Alternobaric vertigo in military divers. *Military Med.* 135:182-185.

78. Wainwright, W. N. 1958. Comparison of hearing thresholds in air and water. *J. Acoust. Soc. Am.* 30:1025-1029.

79. Weaver, E. G., and M. Lawrence. 1954. *Physiological Acoustics.* Princeton, N. J.: Princeton Univ.

80. Whiteside, T. C. D. 1960. The effect of weightlessness on some postural mechanism. Aerospace Med. 31:324.

OSTEONECROSIS

Part #2 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Kent H. Smith, D.V.M., Ph.D. (Chairman)
Director Hyperbaric Research
Virginia Mason Research Center
Seattle, Washington

John L. Heard, M.D.
3437 Prytania Street
New Orleans, Louisiana

Lent Johnson, M.D.
Armed Forces Institute of Pathology
Washington, D.C.

John Paul Jones, Jr., M.D.
Medical and Research Director
Diagnostic Osteonecrosis Center and Research Foundation
Clearlake Oaks, California

J. Leon Sealey, M.D.
Northwest Industrial Medical Clinic, Inc.
Seattle, Washington

Dennis N. Walder, M.D.,
Department of Surgery
University of Newcastle Upon Tyne
England

Work Performed Under Contract #210-75-0078

with the

NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH

and additional support by

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NIH - HEART AND LUNG INSTITUTE

By

Undersea Medical Society, Inc.
9650 Rockville Pike
Bethesda, Maryland 20014

FOREWORD

Under contract with the National Institute for Occupational Safety and Health and with additional support from U.S. Energy Research and Development Administration, National Oceanic and Atmospheric Administration and NIH Heart and Lung Institute, the Undersea Medical Society, Inc., is developing a National Plan for the Safety and Health of Divers in their Quest for Subsea Energy. The study is divided into a number of subject areas each of which is being handled by a small group of scientists expert in the area.

The study was conducted by the "Expert-Authors" in a special work-group meeting on November 10-14, 1975. This study deals with Osteonecrosis as noted in Article I. A. 1. a. Item (2) of the contract.

Paragraph 5 from the same article of the contract requires that we prepare a monograph for each area to "include an indentification of the problem, data considered, list of priorities in each area, research needs and outlines of needed work, and recommendations for accomplishment."

Also, "the monographs shall be capable of 'standing alone' and be supplied for approval and use whenever during the contract the study of a given subject area is completed."

TABLE OF CONTENTS and Organization for

part 2

Osteonecrosis

I. INTRODUCTION 1
II. EPIDEMIOLOGY 2
A. History
B. Classification
C. Registry
D. Data Needed
III. CONSEQUENCES 3
A. Liability
IV. PATHOGENESIS 5
A. Types of Bone Lesions
B. Proposed Etiologies
C. Predisposing Factors
V. TECHNIQUES FOR EARLY DETECTION 9
A. Radiography
B. Radiographic Interpretation
C. Additional Studies
D. Requirements to Improve and Standardize Detection Techniques
VI. PREVENTION 11
VII. TREATMENT 11
VIII. REQUIREMENTS WITH ESTABLISHED PRIORITIES 12
IX. LABORATORIES
X. REFERENCES

I. INTRODUCTION

Skeletal damage (dead bone and crippling arthritis) resulting from pressure changes was first recognized near the beginning of the twentieth century. Despite the steady increase in published information, important facts about the cause, course, and prevalence of osteonecrosis are still unknown. Forty different names have been used to describe this disease since it was first recognized; the term currently used when divers are affected is dysbaric osteonecrosis.

The first description of the disease in a diver was written by Grutzmacher in 1941, but surveys of particular segments of the diving population were not conducted until 1952.

Differences in compression/decompression exposures, inert gases, types of work, and traditional practices all appear to influence the occurrence of this condition. The scarcity of information about the commercial diving population makes any estimate of incidence impossible. Generally, this condition is reported less often in the U.S. diving population than for compressed air workers, for reasons which are not clear. Determining the prevalence of this disease is essential to evaluating its significance. A central registry would provide the information necessary to determine both incidence and prevalence.

Because we lack information regarding occurrence, the commercial diving industry questions the significance of this disease, though there is no disagreement that joint damage is disabling and causes economic loss. The medico-legal aspects of this disease need to be established.* Understanding the differences between compressed air workers and divers, in terms both of anatomical sites and prevalence, may clarify the problem somewhat.

In addition, experimental, clinical, and epidemiological research is needed to enhance our ability to treat and prevent this condition. Several pathologic mechanisms and etiologic agents have been considered, but the details of the causes and course of the disease process need to be clarified. Compression and the duration of exposure to pressure may be causes or contributing factors, but the overwhelming evidence indicates that dysbaric osteonecrosis is decompression-related.

At present, the only way to prevent the disease is to prohibit diving, which is hardly a feasible alternative; we can only guess about other preventive measures. Treatment of advanced stages of the disease by orthopedic intervention is relatively straightforward, but therapy for earlier stages is not available.

---

*For a detailed consideration of legal and compensatory aspects, see Report 6-T.

II. EPIDEMIOLOGY

A. History

Osteonecrosis among compressed air workers was first described by Bornstein and Plate in 1911-12, and in a diver by Grutzmacher in 1941.

Published data from approximately 3,800 professional divers throughout the world show that about 800 had radiological evidence of significant skeletal lesions, 366 of which were in the arm and 233 in the leg. Approximately 300 of these lesions were adjacent to joints. The 3,800 divers comprised four groups: 1) navy divers using standard tables, who had a 2-3% incidence of radiographic lesion changes, 2) 43 divers using experimental tables, who had a 5-8% incidence, 3) commercial divers, among whom the incidence has been reported to range between 3-33%, 4) divers in Japan, using traditional techniques, who have an incidence of osteonecrosis reportedly as high as 40 to 75%.

Over the years, the incidence for commercial divers in the western hemisphere has been reported to range from 3-30%. In the past, the likelihood of lesions increased with the number of years of diving and the depths of dives.

B. Classification

In 1970, the British Medical Research Council's Decompression Sickness Panel formulated a system for the classification of radiographic appearances frequently associated with osteonecrosis (Table 2-1).

Table 2-1. British Medical Research Council's Classification of Bone Necrosis in Compressed Air Workers and Divers

A. Juxta-Articular Lesions

1. Dense areas, with intact articular cortex
2. Spherical segmental opacities
3. Linear opacity
4. Structural failures:
    a. Translucent subcortical band
    b. Collapse of articular cortex
    c. Sequestration of cortex
5. Osteoarthritis

B. Head, Neck and Shaft Lesions

1. Dense areas
2. Irregular calcified areas
3. Translucent areas and cysts

This classification has had wide international acceptance. The classification divides the radiographic changes into two main groups: 1) juxta-articular lesions, which are adjacent to the joint surfaces and which are frequently associated with progressive disability; 2) shaft and neck lesions (medullary) which have rarely been associated with disability. Accurate classification of these radiographic appearances requires proper interpretation and films of good technical quality.

C. Registry

There is a need for a centralized registry to collect data about divers and compressed air workers. Regional examination centers should be established to collect, screen, and forward appropriate data to the central registry. This registry system could be modeled after ALFORD (Appalachian Laboratory for Occupational Respiratory Disease) or the BMRC (British Medical Research Council) Decompression Sickness Central registry. The data base, as a minimum, should include pre-exposure and periodic data from all divers.

D. Data Needed

Suitably designed questionnaires should be developed to provide accurate information about personal, medical, occupational, and diving experience. Problems of confidentiality and informed consent, with minimum personal risk, would have to be resolved before such a self-report system could be put into operation. Additional information should include: 1) initial and periodic certification of divers, and 2) maintenance of a diving log. All professional divers should be certified periodically, just as pilots are; professional participation should be mandatory.

III. CONSEQUENCES

The earliest indication of a bone lesion is a slight change in the radiographic appearance; this is of little significance in itself, but such lesions occasionally lead to permanent and serious disability, depending primarily on the position of the lesion.

Lesions situated in the shafts of long bones have not been reported to extend beyond the metaphysis or involve the cortex of the bone, although such lesions may undergo changes over a period of years. The bone is not weakened by shaft lesions and changes in the lesions are of no consequence, except as indicators of increased risk of additional bone lesions if diving is continued. There are rare reports in the literature of malignant tumors arising from sarcomatous changes occurring in the walls of bone lesions.

If the lesion is situated near a joint, a structural failure may occur. Such failure results in pain and limitation of movement, followed by the development of degenerative arthritis.

Not all juxta-articular lesions deteriorate in this way. Some appear to stabilize; the damaged tissue is apparently repaired. A stabilization may be permanent, or the repair may be inadequate, in which case it will be followed by collapse of the joint surface. At this stage surgical intervention must be considered.

A. Liability

Once a diagnosis of bone damage has been made and the patient is informed, two questions arise. 1) What are the likely consequences in terms of work and ability to earn money? 2) What compensation is available?

At present, most physicians agree that the presence of a juxta-articular lesion is sufficient reason to recommend that those types of diving with which bone damage is associated be discontinued. This is not done because the first lesion will have a better chance of healing, but because there may be an increased risk of getting another symptomatic bone lesion if diving is continued; two damaged joints represent a much more serious disability than one.

In the past, shaft lesions have been taken less seriously than juxta-articular lesions, because shaft lesions had never been known to cause symptoms. However, recent observations suggest that a shaft lesion may predict future bone lesions, one of which might of course be juxta-articular. The presence of malignant changes may alter our current view of the innocuous nature of shaft lesions.

In Great Britain, compensation for injury sustained during work can only be claimed if disability is present. In the United States it is only necessary to establish that injury has occurred, so that a symptomless bone lesion might be grounds for compensation. Skeletal bone damage resulting from work as a diver is classified in the United Kingdom as a form of decompression sickness; as such, it would be notifiable, and if disability were present, compensable under the national insurance plan. It is also possible in both countries for the patient to sue his employer if he believes that there was some negligence associated with his disability; only if this alleged negligence is established will he be eligible for compensation from this source. Good practice should be reflected favorably in actuarial assessments of risk.

If bone necrosis does indeed result from inadequate decompression, it is logical to consider enforcement of the use of some safe decompression table. When tables currently accepted as "safe" are properly applied, however, bone necrosis still occurs; enforcement of the use of such decompression tables may reduce but will not eliminate skeletal damage entirely.

IV. PATHOGENESIS

A. Types of Bone Lesions

It is assumed that all dysbaric bone lesions are the result of loss of blood supply. The loss of blood supply and death of bone and marrow produces no radiologic abnormality in and of itself. Radiologic findings are the result of secondary changes following death of bone and marrow.

1. Areas of dead bone and marrow (infarct) (Fig. 2-1) produce varying secondary changes depending on whether they are located a) adjacent to the joint cartilage (juxta-articular), b) in the cancellous bone and marrow of the metaphysis, or c) in the fatty marrow of the shaft (Fig. 2-2).

a. Juxta-articular lesions may result in buckling of the cartilage (Fig. 2-3) around the margin of the infarct, loss of subchondral plate over the area of infarct (Fig. 2-4), or fracture and collapse of dead bone within the infarct (Fig. 2-5). Any of the three leads to incapacitating arthritis.

b. Lesions of the metaphysis of the bone are often invisible on radiograph, or are marked only by small foci of irregular plaques (Fig. 2-6) caused by reinforcing bone formation at some spot along the margin of the invisible infarct.

c. Shaft lesions (diaphyseal) develop calcification in the ischemic fat and bony reinforcement around the edge of infarcted fat (Fig. 2-7).

2. Radiolucent areas of bone loss beneath the intact articular surface are the result of bone resorption (Fig. 2-8a); no present knowledge or concepts explain their origin and development.

3. Areas beneath an intact articular surface which are wedge-shaped and dense on a radiograph are the result of new bone formation (Fig. 2-8b); no present concepts or knowledge explain their origin and development.

B. Proposed Etiologies

There is general agreement that dead bone and marrow are the result of gas absorption into and release from tissue. There is no agreement about how gas absorption or release results in dead bone and marrow. Several hypotheses have been proposed:

1) Gas dissolved in cells changes the osmotic properties and local circulation

2) Gas bubbles released from tissues anywhere in the body lead to physical obstruction of the small blood vessels of bone

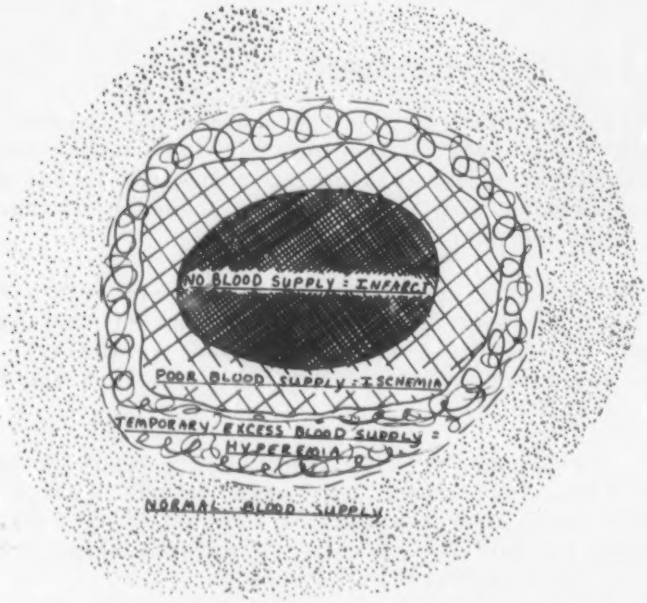

NO BLOOD SUPPLY : INFARCT
POOR BLOOD SUPPLY : ISCHEMIA
TEMPORARY EXCESS BLOOD SUPPLY = HYPEREMIA
NORMAL BLOOD SUPPLY

Fig. 2-1. Zones of altered blood supply

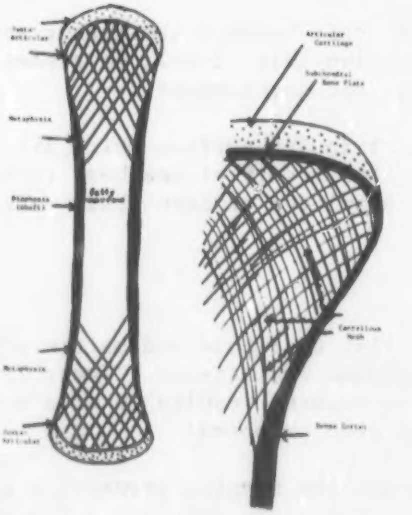


Fig. 2-2. Longitudinal section of long bone and bone end

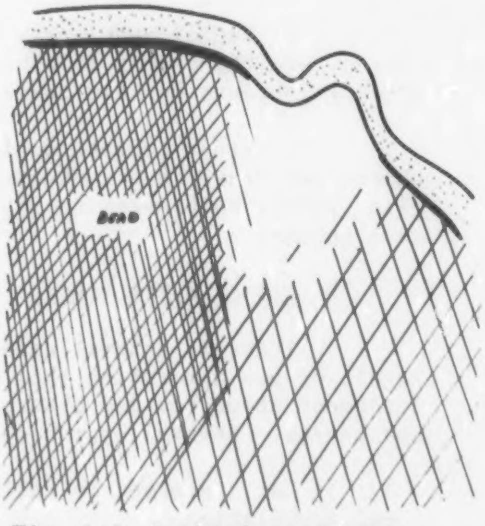


Fig. 2-3. Buckled cartilage due to loss of subchondral plate at edge of infarct

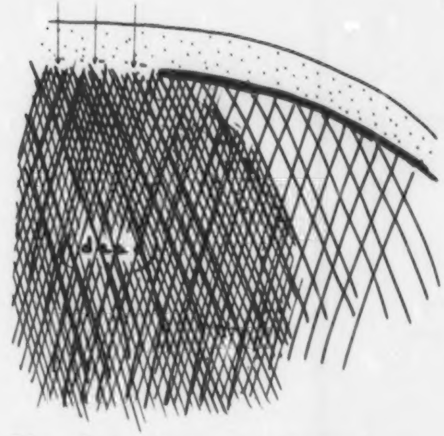


Fig. 2-4. Loss of subchondral plate in infarcted area; cancellous spikes grind into cartilage

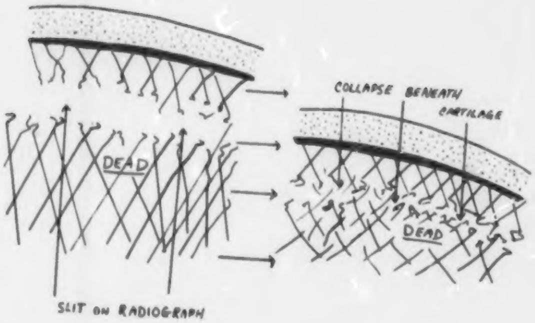


Fig. 2-5. Fractures of dead cancellous bone

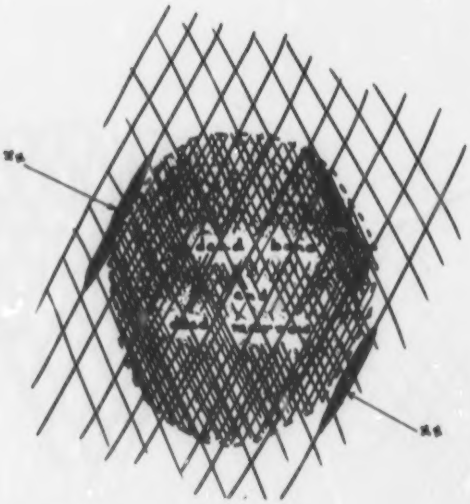


Fig. 2-6. Radiologic appearance of metaphyseal infarct. Arrows point to reinforced plaques of cancellous bone beside infarct

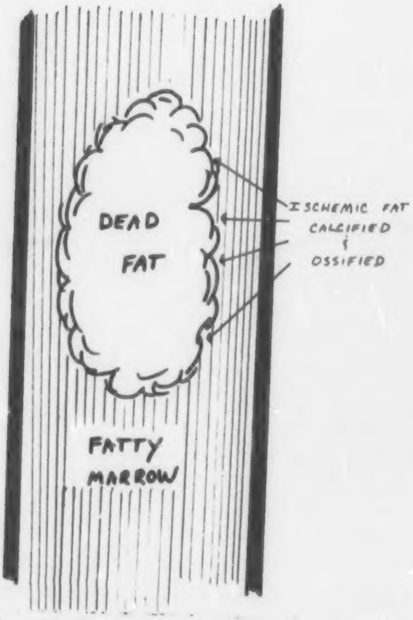


Fig. 2-7. Radiologic appearance of diaphyseal infarct

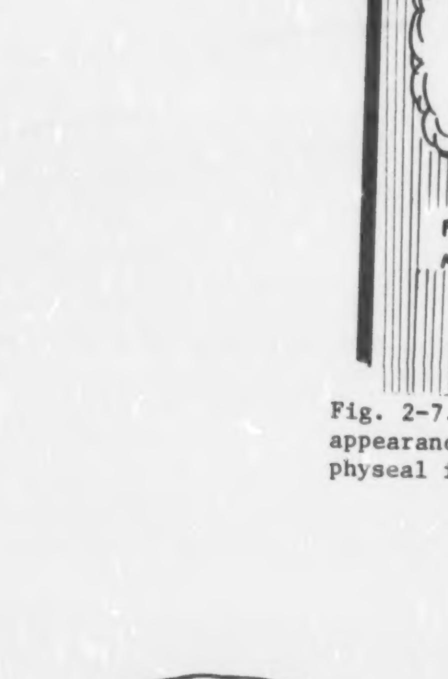


Fig. 2-8a. Radiolucent areas of bone loss

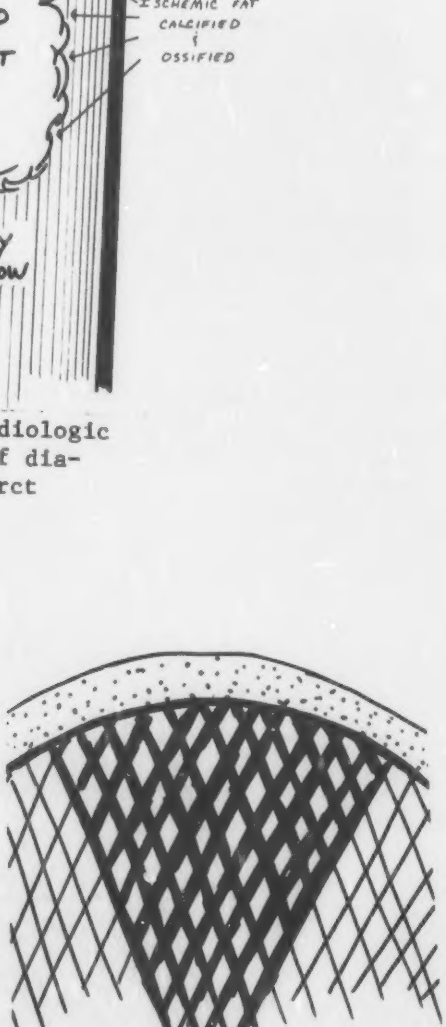


Fig. 2-8b. Sclerotic changes due to new bone formation

3) Gas bubbles (released from tissues anywhere in the body) can damage the lining of small blood vessels, which results in chemical alterations that produce clots in small blood vessels

4) Fat cells anywhere in the body break up upon release of gas, and fat fragments (emboli) obstruct the small blood vessels in bone

5) An intracellular gas phase (expanding gas within cells) expands the fat cells within the bone marrow to the point where, in an unexpandible bone, they cut off their own circulation. None of these hypotheses is entirely satisfactory.

The clarification of mechanisms is essential to both prevention and effective treatment. If osmotic properties are altered, intravenous fluids that balance osmotic properties may be in order. If physical obstruction is the key, gas-disbursing intravenous therapy or sonication might be an approach. If intravascular clotting is the major defect, anticoagulants would be a major consideration. If fat embolism is the problem, intravenous fat solvents might help. If increased intramedullary pressure from expanding fat cells is at fault, surgical relief of local intramedullary pressure may be effective. These are not mutually compatible treatments; clarification of the pathogenesis of osteonecrosis is therefore essential. Until the unique features that underlie the special vulnerability of involved sites are clear, preventive measures will remain imprecise.

C. Predisposing Factors

Major factors increasing the likelihood of such bone damage are: 1) hemoglobinopathies, 2) hyperlipemia and obesity, 3) alcoholism, 4) corticosteroids, 5) occlusive vascular disease.

The first is related to the red-blood-forming marrow, the remaining to changes in the yellow or fatty marrow. Continued diving over many years increases the risk, possibly because there is a normal increase in fatty marrow and decrease of red marrow with age.

The major acute decompression effect on bone is pain, which probably results from increased intraosseous pressure. The lack of correlation between the site of bone pain (the bends) and the site of bone damage on radiographs needs to be explained. This lack of correspondence may be more apparent than real, since many infarcts never become apparent on radiographs, and others become apparent as late as ten years after the causal incident. There have been no autopsy searches for radiologically visible infarcts to assess this problem.

V. TECHNIQUES FOR EARLY DETECTION

A. Radiography

Survey radiographic examination of workers working in hyperbaric conditions is the primary method of detecting dysbaric osteonecrosis. Such an examination should be made as part of the pre-employment evaluation, and as a regular, annual procedure.

These bone surveys are special studies, and should be treated as such; standard radiographic techniques are not adequate. Since the location of osteonecrotic damage is selective, and we know that juxta-articular sites are potentially disabling, radiographic surveys should concentrate on the shoulder, hip, and knee joint areas. In the U.S., a survey should include two rotational views of each shoulder and an anteroposterior and lateral projection of each hip and knee. Proper positioning of the patient and adequate exposure (Bucky high-ratio grid films) using a high kilovoltage technique are necessary to obtain consistent radiographs for accurate interpretation and comparison of serial examinations. The correct combination of film type and screen speed has to be considered, in addition to a properly operated, contamination-free, chemical processing system. A heavily penetrated radiograph has been shown to be most informative, and the usual orthopedic techniques for bone and joint study are not adequate. Primary radiologic gonadal shielding and close collimation to limit the exposure to the beam should always be used; these procedures are essential because of the serial nature of these examinations.

B. Radiographic Interpretation

Standardization of radiological interpretation requires a training program for radiologists involved with osteonecrosis; such a program should include recognition of early lesions, and the use of adequate diagnostic techniques.

C. Additional Studies

Additional information may be obtained by using cylinder cone, spot radiographs, and tomography. These adjuncts are useful in evaluating positive cases detected by bone survey, and are particularly valuable in serial films taken at 2-6 month intervals to establish activity or quiescence of newly discovered lesions.

Tomography is also invaluable in confirming the presence or absence of a lesion in an area of questionable change on a bone survey. Radionuclide bone scans can also be used to study suspected lesions and the stages of development of a lesion.

Other procedures have been used as aids in diagnosis, though these procedures may be more useful in therapy of a lesion than in initial detection. Among these are radioactive phosphorus, tissue-oxygen tension measurements, intraosseous phlebography, and biopsy.

Xeroradiography has been compared with conventional radiography, and the results suggest that xeroradiography is not sufficiently useful as a diagnostic tool to justify the greater radiation exposure accompanying its use.

D. Requirements to Improve and Standardize Detection Techniques

1. An effective program to educate practicing radiologists who will be involved in these studies should be established, so that they will be able to detect the early stages of osteonecrosis.

2. A central registry of all osteonecrosis cases would be invaluable for follow-up studies designed to elucidate the etiology and standardize interpretations of this disease. Data from such studies might also lead to new techniques for early diagnosis.

The training of personnel involved in the early detection of osteonecrosis should be carried out at a regional center which has the appropriate qualifications to accomplish this objective.

VI. PREVENTION

Research to delineate the etiology of dysbaric osteonecrosis and to develop appropriate treatment is essential. Until the etiology is clear, however, it is essential to identify the group of divers with the greatest susceptibility or highest risk of developing osteonecrosis. It will be impossible to prevent osteonecrosis without sophisticated engineering techniques to minimize exposure to the hyperbaric environment. At present, the population of divers at risk includes all those diving to a depth in excess of 33 feet of sea water (fsw). The apparent predisposing factors are: 1) obesity, 2) age, 3) prior decompression sickness, and 4) number, depth, and duration of dives.

VII. TREATMENT

Treatment of symptomatic and asymptomatic lesions should be based on the fact that dysbaric osteonecrosis progresses through stages; management of the disease is different for each stage. Methods of staging the clinical, radiographic, and pathological manifestations of osteonecrosis which affect the humeral and/or femoral heads have recently been developed, and their use should be encouraged. Research is necessary to standardize effective treatment methods for the various lesions of dysbaric osteonecrosis, and to evaluate new or unique methods of treatment.

Stage I

Lesions are asymptomatic. Except for a few focal radiographic changes, the architecture of the bones is normal, without evidence of structural collapse or articular irregularity. At this stage the patient is advised to minimize mechanical stresses to the affected shoulder and/or hip joint by avoiding overhead lifting or the use of pneumatic equipment, or further exposure to the hyperbaric environment. If these procedures are followed, spontaneous healing of the small focal infarctions by revascularization may occur.

Research is needed to test the effectiveness of hyperbaric oxygen, hypothermia, and various pharmacological agents, such as fat-clearing or fibrin-dissolving drugs, in the treatment of Stage I lesions.

Stage II

Stage II lesions are usually asymptomatic, and without gross deformity; they are manifested by coalescence of focal lesions into a single larger lesion. Management of Stage II lesions less than 15 mm in maximum dimension is similar to the treatment of Stage I lesions. Surgical techniques designed to promote revascularization are often indicated for Stage II lesions larger than 15 mm. Accurate diagnosis is essential at this early stage to avoid progressive collapse and irreversible disintegration.

Stage III

Stage III lesions are symptomatic, with irreversible subchondral fractures which lead inevitably to structural collapse and gross deformity. The cartilage on the unaffected side of the joint is still normal, and the joint space is preserved. These lesions require surgical treatment, since they will not heal. Current treatment is to replace the damaged bone end with a prosthesis.

Stage IV

In Stage IV, symptoms are worse and there is evidence of gross articular deformity, which involves both sides of the joint and results in degenerative arthritis. Surgical treatment usually involves total replacement of the affected joint by a prosthesis. Only after a lesion has been classified and graded can a rational plan of treatment be initiated.

VIII. REQUIREMENTS IN ORDER OF PRIORITIES

Research on short- and long-term priorities should be conducted concurrently.

A. Short-Term Priorities

1. Establishment of Central Registry with:
    - a. Regional examination centers
    - b. Certified interpreters
    - c. Mandatory participation of hyperbaric workers
    - d. Standardization and collection of radiographic and occupational data
        - 1) Development and dissemination of radiographical examination techniques

        2) Standardization of radiographical interpretation
        3) Establishment of serial radiographic examination

    e. Periodic reporting of data analysis
    f. Emphasis on determining predisposing factors

2. Research on Additional Detection Techniques

3. Investigation of Treatment of Potentially Reversible Lesions

    a. Physical treatment methods, e.g., recompression, hypothermia
    b. Pharmacological treatment, e.g., fibrinolytic, lipid-clearing agents, and hyperbaric oxygen

B. Long-Term Priorities

1. Research to Establish the Cause of Osteonecrosis

2. Research on the Natural History of Osteonecrosis, to aid in:

    a. Determining age of lesion
    b. Making accurate prognoses
    c. Choice of treatment

        1) Reversible lesions
        2) Irreversible lesions

LIST OF FACILITIES DOING RESEARCH ON OSTEONECROSIS

United States

1. Beth Israel Medical Center
New York, New York

Chryssanthos P. Chryssanthou

2. Diagnostic Osteonecrosis Center and Research Foundation
Clearlake Oaks, California

John Paul Jones

3. Marine Biomedical Institute, University of Texas
Medical Branch, Galveston, Texas

Brian A. Hills

4. Northwest Industrial Medical Clinic
Seattle, Washington

J. Leon Sealey

5. St. Lukes Hospital
Milwaukee, Wisconsin

Eric P. Kindwall

6. State University of New York
Buffalo, New York

S. K. Hong

7. Texas A & M University
College Station, Texas

William P. Fife

8. University of Colorado Medical Center
Denver, Colorado

James S. Miles

9. University of Hawaii
Honolulu, Hawaii

Edward Beckman

10. University of Rochester
Rochester, New York

A. T. K. Cockett

11. Virginia Mason Research Center
Seattle, Washington

Kent H. Smith

12. Schneider and Heard, Ltd.
New Orleans, Louisiana

John L. Heard

Military

13. Armed Forces Institute of Pathology
Washington, D.C.

Lent C. Johnson

14. Naval Submarine Medical Research Laboratory
Groton, Connecticut

Claude Harvey

15. USAF School of Aerospace Medicine, Brooks Air Force Base
San Antonio, Texas

Jefferson C. Davis

United Kingdom

16. University of Newcastle upon Tyne, England
Royal Victoria Infirmary

Dennis N. Walder

Germany

17. Aerztliche Forschungsstelle fuer Druckluftarbeiten
im Institut fuer Flugmedizin der DFVLR, Bonn-Bad Godesberg
West Germany

O. Wunsche

France

18. COMEX
Marseille, France

X. Fructus

19. Laboratory of Applied Physiology, CEMA
Marseille, France

Jacques Chouteau

20. Federation Francaise d'Etudes et de Sports Sous-Marins
Brest, France

P. Merer

21. Centre Hopital, University of Brest,
Brest, France

R. Jaffres

Japan

22. Department of Research and Development, Japan Marine Science and Technology Center

Motohiko Matsuda

23. Institute of Hyperbaric Medicine, Rosaikyokai Hospital
Chiba, Japan

Haruo Saito

24. Kyushu Rosai Hospital
Kitakyushu City, Japan

T. Amako

25. School of Medicine, Department of Hygiene, Tokyo Medical and Dental University, Tokyo, Japan

Ichiro Nashimoto

REFERENCES

1. Beckman, E. L., and D. H. Elliott (Ed.). 1974. Dysbarism-Related Osteonecrosis: A Symposium. National Institute for Occupational Safety and Health, Washington, D.C.

2. Bennett, P. B., and D. H. Elliott (Ed.). 1969. The Physiology and Medicine of Diving and Compressed Air Work. London: Bailliere Tindall.

3. Davidson, J. 1976. Aseptic Necrosis of Bone. New York: Elsevier.

4. McCallum, R. I. 1975. Dysbaric osteonecrosis: aseptic necrosis of bone. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. H. Elliott. 2nd ed. London: Bailliere Tindall.

5. Werts, M. F., and C. W. Shilling. 1972. Dysbaric Osteonecrosis: An Annotated Bibliography With Preliminary Analyses. Biological Sciences Communication Project, The George Washington University Medical Center, Washington, D.C.

SUBTLE PHYSIOLOGICAL CHANGES

Part #3 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Lutz A. Kiesow, M.D. (Chairman)
Director, Experimental Medicine
Naval Medical Research Institute
Bethesda, Maryland

Ralph Brauer, M.D.
Institute of Marine Biomedical Research
Wilmington, North Carolina

Victor Frattali, Ph.D.
Environmental Biosciences Department
Naval Medical Research Institute
Bethesda, Maryland

Richard B. Philp, Ph.D.
Department of Pharmacology
University of Western Ontario
London, Ontario, Canada

Lawrence Raymond, CAPT, MC, USN
Head, Pulmonary Branch
Naval Medical Research Institute
Bethesda, Maryland

TABLE OF CONTENTS and Organization for part 3

Subtle Physiological Changes

I. INTRODUCTION.. 1

A. Subtle Effects

II. RECOMMENDED RESEARCH.. 5

A. Cell Population Dynamics

B. Temperature Regulation in High Pressure Environments

C. Subcortical Effects Associated with the High Pressure Nervous Syndrome

D. Disease Resistance and Wound Healing

E. Nutrition and Metabolism

F. Fluid and Electrolytes

G. Pharmacologic Effects on the Central Nervous System

H. Platelet Changes

I. Alterations in Blood Coagulation

J. Plasma Enzymes

K. Hematopoiesis

L. Changes in other Chemical Elements of the Blood

M. Drugs and Decompression Sickness

III. RESEARCH PRIORITIES...19

IV. FACILITIES...23

REFERENCES...24

I. INTRODUCTION

Most of the reports of the National Plan deal with the technological and physiological problems which presently restrict or impair the efficiency, health, or safety of divers in the field. This report is concerned with the many biochemical and physiological changes whose effects are subtle under present conditions, but which may prove severely limiting or even lethal under the field conditions of the future.

It seems clear that the number of divers, their mobility or independence of surface support, and the depths and duration of dives, will all increase in future underwater operations. These factors emphasize the importance of accurate biomedical data as a basis for the selection of divers, physiological self-monitoring by the diver, and an understanding of the long-term effects of increased exposure to pressure.

With these developments in mind, the committee has attempted to predict which subtle effects may limit the efficiency or jeopardize the safety or health of divers in the future. These may include physiological changes which have long time-constants and are therefore likely to produce cumulative or residual effects, factors which alter the diver's self-perception, and changes related either to greater depths as such, or secondarily to the effects of pharmacological or other agents designed to modify the effects of pressure.

A. Subtle Effects

The following list identifies those effects which are associated with present diving conditions either sufficiently rarely, or to a sufficiently marginal extent, to be considered subtle. The list is arranged according to the sequence encountered in actual diving, from compression and bottom sojourn to decompression and post-decompression.

1. Uniformity of atmosphere during rapid compression
   a. Exaggerated thermal gradients
   b. Non-respirable pockets
2. Transient distortion of alveolar gas composition during rapid compression
3. Changes in cell division rates caused by:
   a. High hydrostatic pressure
   b. Narcotically effective inert gas partial pressure

c. Altered skin or tissue temperatures

4. Changes in hematopoiesis

a. Altered cell population dynamics in various stem cell lines

b. Endocrine response to high oxygen partial pressures

5. Changes in disease resistance and in wound healing

a. Altered immune reactions in high pressure environments

b. Alterations in cell replication rates

c. Alterations in cell replication rates caused by increased oxygen partial pressure

6. Changes in the endocrine system

7. Changes in basal metabolism rate reflecting:

a. Thermoregulatory effects

b. Increased respiratory work at high pressure

c. Direct effect of high hydrostatic pressures on tissue metabolism

d. Effects of high hydrostatic pressures on the central nervous system

e. Biorhythm changes

8. Altered biorhythm reflecting:

a. Changes in exercise regimen

b. Changes in life regimen

c. Changes in central nervous system function under high pressure or as a result of increased partial pressures of narcotic inert gases (changes in sleep patterns).

9. Subcortical High Pressure Nervous Syndrome (HPNS) effects - effects of high hydrostatic pressure on functioning of subcortical centers of the central nervous system, including the ascending reticular formation and perhaps the brainstem centers involved in regulation of autonomic and vegetative functions, such as temperature regulation, fluid balance, and vasomotor tone

10. Altered food acceptability associated with olfactory accommodation, or perhaps with changes in the respired atmosphere

11. Altered effects of drugs in hyperbaric environments attributable to:

a. Altered functioning of central nervous system

b. Altered body metabolism

c. Altered cell replication rates

d. Altered endocrine balance

e. Altered basal metabolism rate

12. Changes in rate and heat of evaporation due to altered solubility of water in high pressure atmospheres, perhaps reflecting changes in molecular aggregation of water vapor

13. Altered temperature perception caused by:

a. Altered sensory input due to distorted temperature gradients throughout the body, including altered relations between hypothalamic and core temperatures

b. Altered central thermoregulatory functions reflecting HPNS effects and/or inert gas narcosis, or interaction between these two

c. Altered evaporation rates

d. Altered balance of modes of heat dissipation in high pressure

14. Fluid and electrolyte balance during immersion, reflecting:

a. Shifts in intracellular/extracellular fluid distribution due to regional hypothermia

b. Shifts in blood volume distribution due to altered gravitational input, and the resulting reflex changes in central fluid and electrolyte regulation

c. Redistribution of blood volumes attendant on increased respiratory resistance

d. Possible direct effects of high hydrostatic pressures on subcortical centers, especially the hypothalamus

15. Sensory deprivation, isolation, and related effects, which reflect:

a. Effective isolation from the environment and substitution of an artificial proximal environment

b. Sensory limitations imposed by the environment, such as reduced gravitational effects and restricted vision

c. Distorted sensory input, e.g., auditory, perhaps thermal

16. Reserve capacity of diver

a. Actual limitations of metabolic reserve due to respiratory limitations and obstruction by protective dress, helmet, and umbilical cord

b. Possible effects of altered physiological or nutritional state resulting in lowered effectiveness

c. Impaired self-judgment, under control of the central nervous system

17. Occult bends - subclinical alteration in tissue function or integrity associated with excessive differential between total tissue gas tension and hydrostatic pressure surrounding a tissue, due to:

a. Change in ambient pressure

b. Change in ambient gas composition, i.e., isobaric bends

18. Post-HPNS depression - effects recorded during early decompression after dives involving HPNS, especially exposures involving a rapid pressure change at the beginning of the decompression, and thus perhaps reflecting a special case

19. Isobaric bends - tissue injury resulting from gas bubble formation associated with counterdiffusion processes

20. Pharmacologic aspects of decompression - interaction of a variety of pharmacologic agents with pathologic or biochemical manifestations of decompression sickness

21. Laboratory criteria for decompression safety using alterations of blood composition associated with the early stages of decompression sickness

22. Incompletely reversed pathophysiologic effects

a. Irreversible changes related to clinical or subclinical bends

b. Residual effects of accommodation to thermal or other environmental stresses of high pressure environment

c. Residual changes in central nervous system function or structure after exposures to conditions producing High Pressure Nervous Syndrome symptoms

II. RECOMMENDED RESEARCH

The sections which follow will explore and make recommendations related to those subtle effects which, in the judgment of this committee, are most likely to pose problems for the safety and health of divers in the future. We have excluded factors, such as thermal protection and HPNS effects on locomotor function, which have been adequately covered in other reports of the National Plan.

A. Cell Population Dynamics

Many tissues of the human body depend for their integrity upon continuous cell divisions that proceed at a more or less constant rate to replace worn out and lost cells and thus maintain a steady state in cell populations. Examples of such tissues include the lining of the gut, the red and white blood cells, and the skin, among many others. Wound healing, similarly, depends to a considerable extent upon cell division to create the pool of cells which bridges structural gaps and re-establishes function. Failure of cell division processes leads to drastic changes in the makeup and relative numbers of the cell populations of the various tissues of the body. This can have exceedingly serious consequences. The best known example of the consequences of impairment of cell division processes are the various stages of radiation sickness.

Three factors in the diver's environment could conceivably affect cell replication processes: 1) regional hypothermia; 2) high hydrostatic pressures; and 3) anesthetically effective inert gas partial pressures. Effects of regional hypothermia appear to be transient and quite mild compared to other cold exposure effects. Residual effects probably make only a marginal contribution to the interaction between body temperature changes and susceptibility to infectious disease. Hydrostatic pressures of 50 ATA or greater have been shown to affect cell replication processes. To date, the experimental data on this subject appear to be confined to work with microorganisms, and to a small extent to studies with tissue cultures from mammalian sources. Hydrostatic pressures of this magnitude affect the mechanics of cell division by disrupting essential structural elements, in particular microtubules. There is increasing evidence that pressures that significantly affect cell replication rates may also impair transfer mechanisms which carry information from the genetic matrix to the systems responsible for the reproduction of specific proteins. The limited data currently available suggest that the effects of high hydrostatic pressures on cell division processes tend to be reversed promptly and completely when pressure returns to lower values. It cannot be assumed, however, that effects produced in more complex systems, in particular in the tissue of animals, will be similarly reversible, since the disruption of normal cell population patterns in coherent tissues may well produce secondary effects which may to a certain degree prove self-perpetuating.

Anesthetically effective partial pressures of inert gases can affect cell population dynamics in two ways: they can interact with hydrostatic pressure effects, as in the case of HPNS, to reduce the magnitude of the effects produced by hydrostatic pressure, or, in the absence of an underlying hydrostatic pressure effect, they can reduce cell division rates, both in microorganisms and in tissue culture preparations. There is some data to suggest that a similar effect can be produced in whole animals. Thus, prolonged exposure to levels of nitrous oxide which produce narcosis comparable to that observed in subjects breathing air at a depth of 300-350 fsw produces significant changes in the number of formed elements of the blood (especially of lymphocytes). At slightly higher levels, changes in the spleen and the lining of the gastrointestinal tract are observed which are strikingly similar to alterations observed in severe radiation sickness. At the present time, data on these phenomena which are applicable to intact mammals are limited. It is possible that the effect of nitrous oxide represents a specifically toxic effect or, more probably, reflects the effects of prolonged anesthesia on cell division processes.

Research to date suggests that these effects are likely to become noticeable only at the upper limits of those pressures and inert gas partial pressures likely to be encountered in diving operations in the foreseeable future. However, it should be reiterated that the evidence currently available is almost exclusively confined to studies on single-celled organisms. It is possible that there are mechanisms by which these effects could be amplified and imprinted more permanently upon the more complex and coherent cell societies which constitute warm-blooded animals and man. It is therefore urgent to undertake research to assess changes in cell population dynamics of subjects exposed to hydrostatic pressures and inert gas partial pressures in the range of pressures and time periods which will be used operationally in the foreseeable future.

B. Temperature Regulation in High Pressure Environments

Much of the discussion concerning thermo-protection of the diver has focussed on the physical factors which affect the balance between heat production and heat dissipation in environments which favor excessive heat loss unless special protective measures are taken.* While such views have proved useful in current diving practice, they are theoretically incomplete. In fact, body temperatures are never uniform; active thermoregulation always involves shifts in temperature gradients within the body. As a result, temperature is a concept applicable only to a relatively small segment of the body which is designated as the core and conventionally includes the brain, heart, and certain viscera. In conditions favoring excessive heat dissipation, either in air or during immersion, core temperatures are maintained at the expense of a progressively increasing peripheral hypothermia which encompasses skin and muscle mass, and results in increasing debilitation of muscular strength and coordination. Furthermore, while temperature regulation is to a large extent autonomically controlled, it is closely coupled with temperature perception. It reflects a combination of core, skin, and central nervous system temperatures, rather than any mean or specific local temperature. Thermal comfort seems to be closely related to mean skin temperature in air, as referenced against some central temperature, most obviously that prevailing in the preoptic anterior hypothalamus. Thermal comfort established by this means is a potentially deceptive index of actual thermal state under special conditions. This is well illustrated by the dangerous third stage of immersion hypothermia, which is characterized by a generalized feeling of comfort and well-being associated with vasodilation which often presages the fatal onset of generalized hypothermia in the cold-exposed swimmer.

In high pressure atmospheres, the situation is rendered even more complex by: 1) the partial temperature clamp on the skin resulting from the high capacity and high heat conductance of the gaseous environment; 2) the greatly increased heat exchange at the level of the respiratory passage, reflecting increased heat capacities of the gases moved with each breath; and possibly 3) by altered relations between moisture content and psychrometric properties of high pressure atmospheres. Greatly increased respiratory heat exchange is the most important of these factors. Because of differences in specific tissue perfusion, this factor can lead to preferential heating or cooling of the central nervous system, with consequent thermoregulatory responses which are not appropriate to the thermal condition of the body as a whole.

It must also be recognized that hypothalamic responses to thermal stimuli are readily modified by variations in neuronal input from other regions of the central nervous system, by changes in the ionic balance in the surrounding environment of the thermolabile neurons, and by a variety of neurotransmitters which may reach the sensitive region either via the blood stream, or as a result of passage of nerve impulses through the appropriate neurons in the vicinity of the critical region. Examples of the degree to which hypothalamic activity may be modified by such factors are the thermoregulatory responses to exercise, and displacements of the thermal set point by deliberate manipulation of the ionic environment. The profound changes in central nervous system excitability which are associated with the effects of high hydrostatic pressures are now well recognized. Present indications are that subcortical centers, including in particular the region in close contact with the hypothalamus, are among those most readily affected. The possibility that significant changes in thermoregulation may be associated with the onset of HPNS changes therefore requires further tests.

---

*For a detailed discussion of thermal problems, see Report 14.

These factors, which could potentially affect active thermoregulation and the perception of thermal comfort or thermal stress, have not been subjected to adequate experimental tests under conditions relevant to deep diving. Without adequate physiological information about temperature regulation, neither the comfort nor the safety of the diver can be guaranteed in the future.

C. Subcortical Effects Associated with the High Pressure Nervous Syndrome

The effects of high hydrostatic pressures on the central nervous system have been reviewed in some detail in another section of the National Plan.* The most dramatic changes noted involve locomotor function, tremor, and generalized convulsions; these changes have attracted the greatest attention of investigators. The limited electrophysiological and reflex information available to date indicates that the preconvulsive changes in central nervous system function are not located in the cortex, the spinal cord, or the peripheral nervous system. These observations do not yet single out specific regions among basal ganglia, midbrain and brainstem structures, though some indications point to the significant role of the ascending reticular formation, at least as low as the pontine region. Hypotheses which explain the neuro-physiological basis of HPNS in biophysical terms are at present inadequate. At the present time, it appears unlikely that HPNS effects are exerted selectively. Rather, the fundamental changes in neuronal properties reflected in HPNS locomotor effects are such that at a given hydrostatic pressure, a large proportion of the neurons making up the central nervous system of mammals are affected to some degree; the apparent prevalence of locomotor changes in the symptoms merely reflects limitations of the experimental data accumulated thus far.

---

*See Report 12.

While generalized autonomic disturbances do not appear to form a major component of acute HPNS, conditions giving rise to HPNS tremors in man are known to be associated with a number of changes in sleep patterns, hormone excretion rates, blood and urinary electrolyte patterns, vigilance behavior, and nitrogen balance. We do not intend to assert that any or all of these changes are necessarily reflections of underlying changes in central nervous system effects attributable to the high pressure nervous syndrome, but the possibility of such a relation cannot be denied on the basis of available data. In fact, animal experiments on temperature regulation and color changes in various species point to a correlation between HPNS development and changes in hypothalamic and hypophyseal function. Furthermore, pharmacologic studies point to the significant role of central nervous system monoamine neurotransmitters in the development of HPNS. In view of the known neuroanatomy of monoaminergic pathways in the central nervous system, these observations underscore even further the likelihood of widespread changes in central nervous system function, involving systems concerned with the regulation and coordination of a wide variety of somatic and visceral functions.

The possible time course of these widespread changes is even less well understood. Compression rate is important in determining the onset and severity of certain HPNS signs and symptoms. It has been pointed out, however, that this relation is not invariable, and indeed, that end points which are highly compression-rate-dependent in one species may prove to be independent of compression rate in another strain or species. In man, the severity of certain HPNS symptoms is markedly increased at rapid compression rates, and shows some degree of accommodation or subsidence when subjects are allowed to remain at a constant pressure for some time. However, HPNS-related symptoms do not entirely disappear, even after one week's sojourn at pressures of 40 or 50 ATA.

Very little data are available concerning residual effects in subjects who have had severe HPNS and then been decompressed successfully. Indications are that the changes may well be readily and completely reversible. Thus, in squirrel monkeys, HPNS convulsion thresholds were found to be highly reproducible in as many as four successive compression/decompression experiments, provided the individual exposures were spaced to allow for full recovery of the animals. Nonetheless, both the character and the scope of these experiments were too limited to permit safe application of the findings to man.

In summary, there is reason to suspect that exposures to high hydrostatic pressures may affect a wide range of regulatory central nervous system functions beyond the locomotor functions studied in detail to date. Under conditions of prolonged exposures to depths in excess of 1,000 fsw, such subtle changes may profoundly affect the health or safety of the human diver. Present information is inadequate to assess the character or the magnitude of such potential effects, or to predict the degree to which any of these effects might prove reversible. In the opinion of the committee, experimental work in this area is needed to determine whether these changes may present a significant potential hazard in future diving operations and to indicate what types of surveillance may be necessary for future subjects of human diving experiments.

D. Disease Resistance and Wound Healing

Under present diving conditions there are changes in the diver's resistance to disease, evidenced by the increased frequency of ear and skin infections. These infections may be caused by altered environmental conditions (high humidity) and may also reflect changes in the host's resistance and effects of the hyperbaric environment on the microorganisms themselves.

In addition, hyperbaria may affect latent infections and what may be called essential physiological infections, such as the intestinal flora, by decreasing the host's resistance or by causing dissemination of microbes and their products. Animal experiments have shown that diving exposure may lead to septicemia resulting from changes in the intestinal walls that allow the passage of bacteria and/or their toxins into the blood.

Similar considerations may apply to aspects of wound healing, where the hyperbaric environment creates new conditions in several ways. These conditions may be abnormal with respect to tissue temperature, changes in hormone levels that are essential to the healing process, and changes in cellular metabolism and growth rates. In addition, wound resistance to topical infections may change drastically, which could seriously interfere with the healing process.

Extending dives to greater depths and longer durations combined with new operational requirements may not only compound changes in disease resistance and wound healing which we are aware of, but changes which are presently unknown may develop. For example, the effects of hyperbaric exposure and increased oxygen partial pressure on the human immune system are largely unknown. Are there losses in antibodies or alterations in antibody production? Do diving exposures lead to the formation of new antigens which may result in auto-immune disease? Does diving exposure result in changes of the gut flora and cause different nutritional requirements? Can the effects of prolonged and extended hyperbaric exposure combined with decompression effects at the tissue level result in a breakdown of naturally confining barriers which may lead to a general bacteremia and perhaps even to septic shock? Are toxic components or contaminants of the diving environment enhancing factors of bacterial or viral toxicities?

Many of these questions can be answered by experimentation with suitable animal models and by a more intensive exploration of the biomedical data of human dives. A detailed investigation of various aspects of disease resistance and wound healing should be undertaken before dives are extended to greater depths and longer durations.

E. Nutrition and Metabolism

Research programs dealing with the nutritional state of the diver in saturated hyperbaric heliox atmospheres have received some attention over the past few years. This research resulted from the finding that consistent weight loss occurs within a few days after extended hyperbaric exposure. With some exceptions, the average weight loss appears to be positively correlated with the depth-duration of a dive, i.e., greater individual losses occur during deep or long dives. Weight loss also appears to be exaggerated when a cold stress is imposed, either by immersion in cold water or exposure to an environmental temperature that is below that of comfort in a dry chamber. Metabolic and nutritional studies have shown that this weight loss occurs despite a food caloric intake that is greater than normal. In 18 saturation dives (dives at sea, dry chamber dives, and dry chamber dives involving immersion in a wet pot) for which caloric intake was either measured or estimated, average weight losses as high as 4 kg were reported. For all of these dives, average caloric intake was not less than 2500 kcal/day, and for most of the dives the amount was greater than 2900 kcal/day. In the Helgoland dive in the North Sea, the greatest weight loss occurred despite a food intake estimated at 6000 kcal/day, an amount that exceeds the recommended allowance for a man involved in very strenuous exercise.

Several explanations for the persistent weight loss during saturation diving have been proposed. These include: malabsorption of food, loss of body water, atrophy and tissue loss as a result of confinement, and a caloric deficit caused by increased energy expenditure or inefficient energy utilization. Evidence indicates that malabsorption is not very likely, because it was determined that fecal caloric loss under hyperbaric conditions is similar to that at ambient atmospheric pressure. A study using an experimental animal model determined that efficiency of utilization of foodstuffs is unaltered during several days' exposure to a high pressure environment. Loss of body water, however, may be a plausible explanation for weight loss during very deep dives. In a study conducted at a depth of 50 ATA, weight loss was presumed to be caused by an initial diuresis resulting either from peripheral vasoconstriction or from changes in intrathoracic pressure due to breathing of dense gases. It was postulated that changes in intrathoracic pressure create a fluid imbalance causing atrial distension, which inhibits antidiuretic hormone secretion (the Gauer-Henry reflex). On the other hand, weight loss accompanied by a mild diuresis during a shallower dive did not alter the degree of body hydration significantly.

Atrophy and tissue loss due to confinement seems to be a very remote possibility, because at least two studies which assessed excretory levels of nitrogenous compounds found that they were not excessive. Body fat stores, however, appear to be mobilized and may well be the principal reason for the losses. When metabolic expenditure calculated from oxygen consumption is compared to available energy derived from diet, a substantial, and as yet unexplained, difference is observed. Energy expenditure does increase under hyperbaric conditions, though not sufficiently to match the energy derived from the food consumed. The quantity required to equate energy expended with energy intake has tentatively been designated an entropy term in metabolism; as such, it may not be measurable by conventional means. Research to examine the effect of hyperbaric conditions on the thermodynamic aspects of metabolic and other biochemical reactions at the molecular and the tissue levels is in order, to elucidate the puzzling observations made to date.

There is other evidence which tends to support the contention that hyperbaric exposure produces undesirable effects on metabolic processes. Clinical and biochemical techniques to assess nutritional status of a whole organism before, during, and after a compression-decompression exposure point to alterations at the molecular level. Specifically, certain enzyme activity levels can be used to assess the adequacy of vitamin nutriture. Given a normally adequate intake of vitamin, any change in enzyme activity level can be used as a measure of the degree of metabolic stress accompanying exposure to environmental stress. One such enzyme, erythrocyte transketolase, whose activity is dependent upon thiamin (vitamin B-1) and related to energy expenditure, decreases in both man and experimental animals following saturation heliox dives (15-50 ATA). Other enzyme systems involved in oxidative metabolism are also dependent upon this vitamin. It is possible that this decrease reflects either an increase in demand for vitamin B-1 and other micronutrients or ineffective utilization of a normally adequate supply.

Other studies have examined plasma levels of related enzymes for indications of incipient cellular damage or malfunction following hyperbaric exposure. While major changes of plasma levels of CK, LDH, GOT (creatine kinase, lactic dehydrogenase, and glutamic-oxalacetic transaminase) and other enzymes are known to be associated with pathological processes, minor but significant elevations of serum CK that are apparently not linked with any manifestation of decompression sickness are often observed during hyperbaric exposures. It has been demonstrated in vitro that decrease in oxygen or glucose availability can cause efflux of intracellular ions and enzymes such as LDH and CK, probably as a result of an inability to maintain adequate cellular levels of ATP (adenosine triphosphate). It is also possible that ineffective utilization of ATP stores in the presence of adequate oxygen or glucose levels may cause egress of cellular components. In either case, elevation of serum CK in the absence of an acute pathological process may result from a decreased availability of metabolic energy during hyperbaric exposure.

In sum, human and animal studies indicate that hyperbaric exposure causes metabolic and nutritional changes. Research to elucidate the mechanisms underlying the phenomena of extended hyperalimentation, weight loss, alterations in fat metabolism, and other cellular changes is needed. Some of these effects are of low magnitude and appear to be reversible upon return to normobaric conditions, but they do add to the stress of saturation diving, and could become significant if functional lesions develop in a tissue or organ.

F. Fluid and Electrolytes

Maintenance of the proper distribution of water and electrolytes among plasma, tissue spaces, and cells is absolutely essential for normal bodily function; it is therefore essential to identify potential limitations that may arise from fluid or electrolyte imbalance. Cellular metabolism is very sensitive to variations in volume and composition of the intracellular fluid, which depend in turn upon the state of the extracellular fluid. The amount of water required by the body is determined by the quantity needed to maintain the volume and osmotic pressure of the body fluids and to replace water lost by excretion through the skin, lungs, and kidney, and by elimination of waste. Water is obtained from imbibed water and beverages, the moisture content of foods, and the oxidative metabolism of foodstuffs, while the kidney has a dominant role in the maintenance of water and electrolyte balance.

Numerous observations made on man and experimental animals indicate that the various environmental factors encountered in diving can alter the normal modes by which fluid balance is achieved. In several helium-oxygen dives at depths or pressures as great as 50 ATA, an increase in urine output has been observed. Cold exposure, either with or without water immersion, may be partially responsible for the hyperbaric diuresis effect, but other environmental conditions encountered in diving situations cannot be discounted as contributors to the effect. Renal function was assessed and the urinary excretion of aldosterone and antidiuretic hormone were measured during a dry-chamber 10-day dive in helium-oxygen at 7 ATA. Results from the study showed a reduction in urinary creatinine excretion, and decreases in urinary osmolality and tubular resorption of sodium and potassium. Although daily balances of sodium and potassium were unaffected, a pronounced reduction in daily water balance indicated that a state of negative water balance had occurred during the course of the dive. On the other hand, other indices of dehydration, such as serum protein and osmolality, weight, and excretion of antidiuretic hormone and aldosterone showed little or no change over the same time period. These facts indicate that this negative water balance resulted from a reduction in water diffusion from the skin and respiratory surfaces, which caused the observed diuretic response. In an amplified study of the same biological parameters during a 19-ATA helium-oxygen saturation dive, quantitatively similar results were obtained. Further, total body water measurements, as determined by a deuterium oxide dilution experiment, indicated that even with an observable weight loss the degree of body hydration remained essentially constant throughout the course of the dive. Based on this and the previous study, hyperbaric diuresis apparently did not reflect initiation of a dehydration process.

Other reports have addressed the problem of fluid and electrolyte homeostasis using certain hematological parameters to indicate fluid and electrolyte shifts among the various body spaces and compartments. Hemodilution or hemoconcentration, as assessed by a respective decrease or increase in packed-cell volume, has been used as such an indicator. While several investigators have reported a decrease in packed-cell volume during or after air saturation dives, one group observed an increase and attributed it to dehydration. Similar studies of hematological parameters during heliox dives do not agree sufficiently to allow an unambiguous assessment of the response to hyperbaric exposure. In addition to volumetric changes, alterations in packed-cell volume are governed by hematopoiesis and cell destruction; other environmental conditions that effect cell production or destruction cannot therefore be overlooked.

With the exception of those instances involving pathology related to compression or decompression, the observations to date on fluid and electrolyte balance from helium or nitrogen saturation dives indicate that sustained pressurization for as long as 30 days is unlikely to produce a serious or hazardous effect in man.

G. Pharmacologic Effects on the Central Nervous System

As dives are extended to longer durations and diver's tasks become more sophisticated, the use of drugs which affect the nervous system becomes more likely; the likelihood of both antagonism and synergism between drug effects and the effects of the hyperbaric environment increase proportionately. For example, animal experiments many years ago showed that an increase in pressure to 136 ATA caused a complete reversal of ether anesthesia in tadpoles. Since then, a pressure reversal of the effects of such anesthetic agents as halothane, sodium pentobarbital, and thiopental have been demonstrated. These reversal effects are correlated with pressure and are also reversible. These observations were also extended to gaseous agents like nitrous oxide, sulfur hexafluoride, and carbon tetrafluoride, all of those effects were linearly antagonized by high pressure helium. The effects of some local anesthetics and pressure were synergistic. It is safe to say that an increase in pressure affects the activity of drugs acting on the central nervous system; research into these effects should be undertaken.

H. Platelet Changes

There is strong evidence that platelets are involved in decompression sickness. That platelets adhere and aggregate on the bubble surface has been demonstrated, and platelet microthrombi have been found in severe cases of decompression sickness in experimental animals. A thrombocytopenic response to compression and decompression in man has been observed in conjunction with several dive profiles, largely in the absence of any overt signs of decompression sickness. Preliminary evidence indicates that the extent of platelet loss in man may be influenced by the state of the individual's platelet population, so that subjects with an inherent platelet defect may be less likely to lose platelets, while those with highly active platelets (as determined by in vitro tests of platelet function) may lose more than normal subjects.

Since blood samples collected on the bottom several days into a saturation dive do not reveal any significant change in the circulating platelet count, it must be assumed that platelet loss is a decompression-associated phenomenon. There is also evidence indicating that the rate of platelet turnover increases following decompression, so that the actual consumption of platelets could be considerably greater than the count alone would indicate. Information about the loss of platelets in clinical cases of decompression sickness is very limited. Current evidence suggests, however, that the greater the risk of decompression sickness in a particular dive, the greater the loss of circulating platelets. Several laboratory tests also indicate that normal platelet function is markedly altered by decompression. In view of the established role of platelets in thrombosis, the possibility that this loss of platelets is the result of the formation of microthrombi cannot be discounted. Controlled, double-blind trials with experimental anti-platelet drugs (i.e., drugs which are capable of inhibiting platelet function in in vitro tests) have shown that the post-decompression loss of platelets in divers can be inhibited or blocked by such agents. Thus if the formation of platelet microthrombi does play a role in the pathogenesis of decompression sickness, there is a real possibility that pharmacological adjuncts to recompression therapy may have a clinical role.

I. Alterations in Blood Coagulation

It would appear that compression-decompression may be associated with the development of a hypercoagulable state, evidence of which may be detected in the absence of overt signs of decompression sickness, providing the screening procedures are adequate. Such shifts toward increased activity of the hemostatic mechanism do not usually exceed normal physiological limits in man, but they may represent a prodromal state. Early animal experiments suggested that the hyperbaric environment itself might set the stage for hyperactivity of the clotting system, which is subsequently triggered by too-rapid decompression. Experiments with air-injected rabbits, however, indicated that the presence of an air-blood interface alone will activate the hemostatic mechanism. To date, little evidence is available concerning the state of the hemostatic process in individuals suffering from Type I or Type II bends. It may be that the changes are too subtle to detect unless normal, pre-dive base-line values are available. However, as the depth and duration of operational diving are extended, the significance of the augmented activity of the clotting system may increase dramatically. Little is known of the effects of deep saturation or artificial gas mixes on these parameters.

J. Plasma Enzymes

The knowledge that numerous pathological states induce cell damage and the release of intracellular isoenzymes prompted hyperbaric experiments to determine whether hyperoxia and/or decompression caused sufficient cell damage to yield detectable increases in blood enzyme levels. Results to date indicate two main types of change: moderate elevations in some enzyme levels have been detected during saturation dives, and may be related, at least in part, to circadian rhythms; slight but significant declines in levels of several plasma enzymes have been noted in divers over a period of two to four days following saturation diving. The significance of these subtle changes is still unclear. Of greater importance is the observation that divers who have suffered an attack of decompression sickness, or who have participated in a dive in which decompression sickness occurred in another diver, have shown marked and significant elevations in plasma enzymes levels, including creatine kinase, lactic dehydrogenase, and glutamic-pyruvic transaminase (CK, LDH, and GPT). One subject who suffered oxygen convulsions during a saturation dive also showed elevations of these enzymes and glutamic-oxalacetic transaminase (GOT). Elevations of these enzymes did not occur until 12-48 hours after the traumatic event, a situation similar to that seen clinically in conditions such as myocardial infarction. The usefulness of these enzymes as diagnostic aids in decompression sickness is therefore somewhat limited. However, the detection of elevated levels in asymptomatic individuals indicates that significant tissue damage can occur without the association of pain or other clinical signs of decompression sickness, and suggests that "silent" or occult bends are a real concern.

K. Hematopoiesis

Hyperoxia is known to increase red cell destruction and may depress erythropoiesis as an adaptive response to the increased oxygen tension in the blood. Some workers feel that a PO2 of 300 mmHg (0.4 ATA) is probably the threshold for the antihematopoietic effect of oxygen. However, the toxic effects of oxygen are known to be time dependent as well as partial-pressure dependent, and with longer saturation exposures any oxygen tension in excess of normal (150 mmHg or 0.2 ATA) may have deleterious effects. A reduction in red cell count during and after saturation diving, both with air and with helium-oxygen, has frequently been observed. Red cell counts may be reduced not only by increased destruction and decreased production, but also by dilution if extra-vascular fluid moves into the vascular space. Since oxygen tension is usually regulated within "safe" limits, it may be that the apparent anemia observed during and after saturation diving is largely a hemodilution effect. The question of the effects of long-term saturation exposures on hematopoiesis is unanswered, and will remain so until more sophisticated studies of blood volume and red cell turnover are conducted. The use of ^{51}Cr-labeled red cells and ^{125}I-labeled albumin might shed additional light on this subject, as would reticulocyte counts.

L. Changes in Other Chemical Elements of the Blood

It should be noted that changes in a variety of blood components have been observed in association with compression and decompression. These include cortisol, catecholamines, angiotensin I, immunoreactive proteins, total plasma proteins, and plasma lipids. The significance of these changes is obscure and requires additional work.

M. Drugs and Decompression Sickness

Current clinical usage of drugs in the symptomatic treatment of decompression sickness has been discussed in another report.* On the basis of animal experiments and preliminary studies of divers, it is possible to construct a working hypothesis which incorporates many of the observations discussed above. There appears to be a substantial relationship between decompression, particularly hazardous decompression, and the observations of thrombocytopenia, increased fibrin formation, and hemoconcentration. It now appears highly likely that most decompressions from any significant depth are accompanied by some degree of bubble formation, and the occurrence of decompression sickness is probably dependent upon the size, frequency, and location of the bubbles. Evidence from animal experiments strongly suggests that the blood reacts to the intravascular bubble in the same fashion as it would to any other foreign surface. A layer of protein, probably fibrinogen, is deposited at the blood-bubble interface, as are coalesced plasma lipids. The protein molecules, oriented with their hydrophilic moieties toward the plasma, present a thrombogenic surface which attracts platelets. In extreme situations, this leads to platelet aggregation and the release of clotting agents, such as platelet phospholipid. This bubble membrane may be stripped off to serve as a locus for additional platelet aggregation. These effects, together with stasis of the blood in occluded vessels, may activate the fibrin-clotting system.

The hemoconcentration which has frequently been observed in association with severe decompression sickness is thus probably caused by the extravasation of fluid. The incorporation of plasma lipids into microthrombi has been noted, and would account for the reduction of plasma lipid levels which has been observed in experimental decompression sickness and, to a lesser extent, following decompression of human subjects. The occurrence of lipid emboli in severe decompression sickness is well documented, and could also be related to the coalescence of plasma lipids. A complex interrelationship also exists between plasma lipids, platelet adhesiveness, and the blood clotting system.

---

*See Report 11.

On the basis of this hypothesis, it would appear that anticoagulants, anti-platelet agents, and fibrinolytic agents might play an adjunctive role in the therapy of severe decompression sickness. Some benefits have been claimed for heparin, but its use remains controversial because of the potential hazard of hemorrhage. Low molecular weight dextran is currently popular because of its relative safety and because it is known to inhibit platelet adhesiveness. Experimental anti-platelet agents have not been used clinically, but some have been shown to lower the incidence of decompression sickness in animal tests and to inhibit post-decompression thrombocytopenia in divers. This group of drugs probably holds the greatest interest for the future. Animal tests with fibrinolytic agents have been disappointing.

Some mention should be made of the possible role of vasoactive peptides in decompression sickness. Bradykinin and a substance identified as Smooth Muscle Activating Factor (SMAF) have been implicated in the pathogenesis of decompression sickness, and drugs which antagonize these substances have shown dramatic, protective effects in animal models of decompression sickness. This area of basic research requires much more investigation.

Some specific questions which remain to be answered are:

1) Do "silent" bends occur? That is, can there be significant damage to organs and tissues in the absence of overt signs or symptoms?

2) Does the occurrence of repeated minor tissue insults, as suggested by loss of platelets, increased clotting-factor turnover, and elevated plasma enzymes have deleterious consequences for the diver? This would bear on repetitive and long-term saturation diving, and possible residual and cumulative effects.

3) Would the use of more specific isoenzyme studies pinpoint the location and extent of tissue damage more accurately than gross enzyme determinations do?

4) Early decompression tables used the incidence of bends, i.e., presence or absence of pain, to determine success or failure of a table. Despite refinements based on mathematical predictions of inert gas diffusion and transport, this remains the sole criterion of success to this day. More recently, the advent of Doppler bubble monitoring has made it possible, in theory, to devise tables which

are free of detectable bubble formation. Could biochemical monitoring, i.e., use of enzymes studies, platelet studies, and coagulation studies, provide an even more sensitive technique for establishing the safety of a decompression profile?

5) Is there a role for the use of anti-platelet drugs, or other agents, in the prophylaxis and/or treatment of decompression sickness?

6) Does the apparent hemodilution observed in saturation diving reflect suppression of hematopoiesis or fluid shifts? How does it relate to urine and electrolyte excretion?

To answer these questions, both animal experiments and human studies are necessary. Whenever it is ethically and logistically possible, such studies should be conducted in human subjects using both experimental and operational diving conditions. It is safe to say that thousands of man-hours of experimental diving have been conducted without any effort to collect the kinds of physiological and biochemical data which are essential to answering these questions. We strongly recommend that whenever experimental chamber dives are planned, every effort be made to measure as many of these parameters as practicable, and that when local expertise or equipment is lacking, another center be recruited to participate in the study. The efficiency of this approach has already been demonstrated.

Laboratory observations should also be made in clinical cases of bends whenever possible. We recognize that many of these cases occur far from laboratory facilities, and the urgency of the situation often precludes intensive investigation. Nevertheless, simple instrumentation is available which is capable of measuring plasma enzymes, hemoglobin, cholesterol and a variety of other blood chemical parameters. It is possible to establish a very useful field laboratory for a capital cost of $3,000 or less. Furthermore, many physicians involved in the treatment of decompression sickness do not at present avail themselves of local diagnostic facilities. The establishment of a central bank for this type of data should be considered, possibly through the offices of the Undersea Medical Society. Until this is done, the progression of deeper and longer dives will take place in a biomedical vacuum.

III. RESEARCH PRIORITIES

Research priorities in the areas of subtle physiological changes can be divided into four major categories. The categories are ranked in order of priority, but it is difficult to distinguish between priorities within each category.

The committee arrived at these priorities in the following way: the biomedical effects associated with each stage of the diving process, i.e., compression, bottom time, and so forth, were arranged across the top of the matrix shown in Table 3-1. Factors of the diving environment are arranged in nine categories along the side of the matrix. If there is a significant interaction between operational factor and biomedical effect, a "+" appears in that section of the matrix. A question mark indicates a possible interaction between factor and effect.

Table 3-2 was derived from the matrix in the following manner: The sum of "+'s" for each biomedical factor (a score of 1/2 was given to each "?") was multiplied by a weighting factor (column 3), which reflects the committee's judgment of the significance for diving of that particular biomedical effect. The product of this operation is a numerical score (column 4) which is the priority given to that subtle physiological effect.

These effects were then arranged in priority categories, based on total priority score. The first category of priorities comprises three research areas, i.e., research into the reserve capacity of divers, detection and effects of occult (silent) bends, and changes in disease resistance and wound healing.

The second category deals with: research on the subcortical High Pressure Nervous Syndrome; the occurrence and effects of altered cell population dynamics; investigations of hormonal changes during hyperbaric exposure; studies of the reversibility of pathophysiological changes that may result from diving; and research on thermoregulation and temperature perception during dives.

The third category of priorities consists of investigations in the area of hyperbaric pharmacology, particularly as it relates to decompression. Other research topics which fall within this category are: efficacy and interactions of pharmacologic agents under hyperbaric conditions; changes and alterations in hematopoiesis; altered biorhythms; the possible development of laboratory criteria for diver selection; and the detection of physiological effects in divers, which should include concurrent studies of changes in basal metabolism.

The fourth and lowest category of priorities represents an investigation of the effects of sensory deprivation and isolation, changes in the palatability of food, the effects of alterations and changes in fluid and electrolyte balance in divers, and the effect of CO_2 retention. In addition, the relations between psychrometry and thermocomfort, the phenomenon of chamber layering, the occurrence and effects of isobaric bends, and the possibility of post-HPNS depression, should be investigated.

Table 3-1. Interactions between biomedical and operational factors

		Compression Stage		On the Bottom/Dry											In Water		Decompression						After-effects
		1. Layering Effects	2. CO_2 Retention	3. Altered Cell-population Dynamics	4. Hematopoiesis	5. Disease Resistance/ Wound Healing	6. Endocrine Changes	7. Basal Metabolic Rate	8. Altered Biorhythms	9. Subcortical HPNS	10. Altered Taste/ Food Palatability	11. Hyperbaric Pharmacology	12. Psychrometric Effects of HP	13. Temperature Perception/ Regulation	14. Fluid & Electrolyte Shifts/Immersion	15. Sensory Deprivation/ Isolation	16. Reserve Capacity	17. Occult Bends	18. Post-HPNS Depression	19. Isobaric Bends	20. Pharmacology of Decompression	21. Laboratory Criteria/ Decompression Safety	22. Reversibility of Patho-physiological Effects
I.	PRESSURE/GAS COMPOSITION																						
	a. Hydrostatic Pressure >25 atm	+		+	?	+	?	+	+	+	+	+	+	+				+	+	+			+
	b. Nitrogen pN_2 >3 atm			+	?	+	?	+	+		+	+											
	c. Oxygen pO_2 >0.4 atm			+	+	+	?	?												+			
II.	DIVING MODE																+						+
	a. Saturation/Chamber			+	+	+	+		+	+	+	+	+	+	+			+	+	+	+	+	+
	b. Excursion	+	+			?	?			+		+		+	+	+	+	+	+	+	+	+	
	c. Repetitive	+	+			?	?			?		+		+	+	+	+	+		?	+	+	+
III.	THERMAL EFFECTS																						
	a. In Chamber	+	+			+	+			+	+		+	+			+				+		
	b. In Water		+			+	?			+		+		+	+	+	+						
IV.	LEVEL OF SURFACE SUPPORT	+	+				+		+		+			?		+	+	?				?	
V.	VEHICULAR SUPPORT						?	+		?				+	+	+	+						
VI.	MISSION FACTORS																						
	a. Stress	+	+			+	+			+	?			+	+	+	+	+					
	b. Physical Effort Required		+				+			+	+		+	+	+		+	+					
	c. Orientation & Communication Limitations		+				?		?	?			+			+							
VII.	DIVER CONDITION FACTOR																						
	a. Motivation						?		+	+	+		+	+		+	+						
	b. Subclinical or Chronic Disease			+	+	+	?	+	?	?			+	+	?	?	+	+					
	c. Sensory Acuity						?		+	?	+		+			+	+						
VIII.	TIME DEPENDENCY OF EFFECTS																						
	a. Residual Effects			+	?	+	?			?			?		?			+	?	?	?	?	+
	b. Cumulative Effects			+	?	?	?	?		?					?			+	?		?	?	+
IX.	DIVER SELECTION CRITERIA																						
	Physiological, Biochemical & Behavioral			+	?		?	?	?	?												?	+

Table 3-2. Priorities for Subtle Physiological Effects

	Biomedical Factors	No. in Table 3-1	Number of Interactions	Weighting Factor	Priority Score
I	Diver's Reserve Capacity	16	12	3	36
	Occult Bends	17	9.5	3	28.5
	Disease Resistance and Wound Healing	5	10.5	3	31.5
II	Subcortical HPNS	9	12	2	24
	Altered Cell Population Dynamics	3	8	3	24
	Endocrine Changes	6	12	2	24
	Reversibility of Pathophysiological Changes	22	7	4	28
	Thermoregulation and Temperature Perception	13	11.5	2	23
III	Hyperbaric Pharmacology (Decompression)	20	5	4	20
	Hyperbaric Pharmacology (Interactions)	11	6	3	18
	Hematopoiesis	4	5 1/2	3	16 1/2
	Altered Biorhythms	8	7 1/2	2	15
	Laboratory Criteria	21	5	2	10
	Basal Metabolism	7	5 1/2	2	11

Table 3-2 Priorities for Subtle Physiological Effects (Cont'd.)

	Biomedical Factors	No. in Table 3-1	Number of Interactions	Weighting Factor	Priority Score
IV	Sensory Deprivation and Isolation	15	9.5	1	9.5
	Palatability of Food	10	8.5	1	8.5
	Fluid and Electrolyte Balance	14	8.5	1	8.5
	CO_2 Retention	2	8	1	8
	Psychrometry and Thermal Comfort	12	7.5	1	7.5
	Chamber Layering	1	6	1	6
	Isobaric Bends	19	5	1	5
	Post-HPNS Depression	18	4	1	4

IV. FACILITIES

Because the range of biomedical topics subsumed under the heading of subtle physiological effects is so broad, it is impossible to designate specific laboratories to carry out the research which we have recommended in this report. The committee recommends a different approach, one that has worked well in other areas of marine science, such as hydrographic ships and underwater research habitats. We suggest that the experts and equipment necessary to attack a particular problem be assembled at a hyperbaric facility capable of supplying the technological support and the experimental subjects required for the research.

The scientists involved in such research could be drawn from government, university, and private institutions, and their diverse specialties should allow experiments to be designed which would investigate more variables simultaneously. The increased "yield" of research designed in this way should more than offset the per diem personnel costs. Major hyperbaric research facilities would thus become national facilities, and investigators would have access to these facilities not as guests, but as principal investigators.

REFERENCES

1. Ackles, K. N., A. Korey, M. Moschos, and L. J. McBurney. 1974. The effect of repeated hyperbaric exposure on blood platelets in man. (Abstract) Undersea Biomed. Res. 1:A21-22.
2. Balouet, G., L. Barthelemy, J. Parc, A. Michaud, J. Le Chuiton, and J. P. Leroy. 1974. Lesions infra-cliniques chez des animeaux soumis a des plongees profondes experimentales. Pathol. Biol. 22:23-28.
3. Bove, A. A., J. M. Hallenbeck, and D. H. Elliott. 1974. Changes in blood and plasma volumes in dogs during decompression sickness. Aerospace Med. 45:49-55.
4. Chryssanthou, C., F. Teichner, and M. Koutsoyiannis. 1974. Studies on dysbarism. V. Prevention of decompression sickness in mice by dimethothiazine. Aerospace Med. 45:279-282.
5. Elliott, D. H., J. M. Hallenbeck, and A. A. Bove. 1974. Acute decompression sickness. Lancet 2:1193-1199.
6. Freeman, D., and R. B. Philp. Blood enzyme and hematological changes associated with decompression sickness in rats. (Abstract) Undersea Biomed. Res. 1:A22.
7. Le Guenedal, J. Y. 1974. Activites enzymatiques seriques et bilan ionique au cours d'une plongee fictive en helium-oxygene a 26 ATA. Cent. Etude Rech. Biophysiol. Appl. Mar., Rept. CERB 74-10.
8. Hallenbeck, J. M., A. A. Bove, R. B. Moquin, and D. H. Elliott. 1973. Accelerated coagulation of whole blood and cell-free plasma by bubbling in vitro. Aerospace Med. 44:712-714.
9. Inwood, M. J. 1973. Experimental evidence in support of the hypothesis that intravascular bubbles activate the hemostatic mechanism. Proc. Intern. Symp. Blood-Bubble Interactions.
10. Jacey, M. J., D. V. Tappan, and K. R. Ritzler. 1974. Hematological responses to severe decompression stress. Aerospace Med. 45:417-421.
11. Martin, K. J., S. P. Gray, and G. Nichols. 1973. Effect of a short simulated dive on selected blood constituents in man. Aerospace Med. 44:516-522.
12. Martin, K. J., and G. Nichols. 1974. Serum creative phosphokinase in man during diver training. Aerospace Med. 45:67-71.
13. Murray, R. D., G. M. Adams, and P. A. Miles. 1974. Shallow habitat air dive I: Selected serum protein responses. (Abstract) Undersea Biomed. Res. 1:A31.
14. Philp, R. B. 1974. A review of blood changes associated with compression-decompression: relationship to decompression sickness. Undersea Biomed. Res. 1:117-150.
15. Philp, R. B., D. Freeman, and L. Francey. Hematology and blood chemistry in saturation diving. II. Open-sea vs. hyperbaric chamber. Undersea Biomed. Res. 2:251-266.
16. Philp, R. B., D. Freeman, L. Francey, and K. N. Ackles. 1974. Changes in platelets and other blood parameters following a shallow, open-sea saturation dive. Aerospace Med. 45:72-76.
17. Philp, R. B., D. Freeman, L. Francey, and B. Bishop. 1975. Hematology and blood chemistry in saturation diving. I. Antiplatelet drugs, aspirin and VK744. Undersea Biomed. Res. 2:233-250.

18. Philp, R. B., M. J. Inwood, K. N. Ackles, and M. W. Radomski. 1974. Effects of decompression on platelets and hemostasis in man and the influence of anti-platelet drugs (RA233 and VK744). Aerospace Med. 45:231-240.
19. Powell, M. R., G. F. Doebbler, and R. W. Hamilton. 1974. Serum enzyme level changes in pigs following decompression trauma. Aerospace Med. 45:519-524.
20. Raymond, L., J. Sode, H. C. Langworthy, J. Blosser, and R. E. Johnsonbaugh. 1974. Increase in plasma growth hormone concentration: a new effect of helium breathing. Undersea Biomed. Res. 1:91-98.
21. Saumarez, R. C., J. F. Bolt, and R. J. Gregory. 1973. Neurological decompression sickness treated without decompression. Br. Med. J. 1:151-152.
22. Valeri, C. R., H. Feingold, C. G. Zaroulis, R. L. Sphar, and G. M. Adams. 1974. Effects of hyperbaric exposure on human platelets. Aerospace Med. 45:610-616.
23. Warren, B. A., R. B. Philp, and M. J. Inwood. 1973. The ultrastructural morphology of air embolism: platelet adhesion to the interface and endothelial damage. Br. J. Exp. Pathol. 54:163-172.
24. Widell, P. J., A. A. Pilmanis, L. W. Chapman, V. M. Pilmanis, and R. R. Given. 1973. Physiological effects of saturation diving: oxygen toxicity, stress and fluid volume regulations. Hydro-Lab J. 2:57-72.

RESPIRATORY/PULMONARY FUNCTION IN HYPERBARIC EXPOSURES

Part #4 of the

National Plan for the Safety
and Health of Divers in their Quest
for Subsea Energy

Produced by:

Herbert A. Saltzman, M.D. (Chairman)
Director, F. G. Hall Laboratory for Environmental Research
Duke University Medical Center
Durham, North Carolina

Leon D. Farhi, M.D.
Department of Physiology
State University of New York
Buffalo, New York

Capt. William H. Spaur, M.C., U.S.N.,
Senior Medical Officer
Navy Experimental Diving Unit
Panama City, Florida

Lawrence D. H. Wood, M.D.
Respiratory Clinical Investigation Unit F-2
Health Sciences Center
Winnipeg, Manitoba, Canada

TABLE OF CONTENTS and Organization for part 4

Respiratory/Pulmonary Function in Hyperbaric Exposures

I. INTRODUCTION 1

II. REVIEW OF COMPLETED INVESTIGATIONS 1

A. Control of Breathing

B. Pulmonary Mechanics

C. Gas Exchange

D. Performance

III. RECOMMENDATIONS 5

A. Introduction

B. Performance in the Water

C. Effects of Hydrostatic Pressure

D. Tissue Respiration

E. Effects of Carbon Dioxide

F. Pulmonary Mechanics

1. Statics
2. Dynamics

G. Oxygen Consumption

H. Other

IV. LABORATORIES INVOLVED IN RESPIRATION AND PULMONARY FUNCTION RESEARCH RELATED TO HYPERBARIC EXPOSURES 9

REFERENCES 12

APPENDIX A

APPENDIX B

I. INTRODUCTION

The sub-committee has tried to provide an accurate assessment of available reference material and recent observations that pertain to human respiration during hyperbaric exposures. Our intent was to report the present level of knowledge, to point out apparent limits imposed on human diving by respiration, and to identify crucial gaps which merit further investigation. To provide the most accurate assessment possible, the sub-committee has included references from the open literature, technical reports, and some recent but as yet unpublished material in the reviewed data base. For further information concerning unpublished data the reader is referred to the authors cited in the bibliography. We did not include certain papers which have been superseded, and some whose results contradict the bulk of available evidence. In the latter instance, artifacts usually accounted for the findings.

Finally, we acknowledge our personal limitations and biases, and regret that all the potentially pertinent references from this vast field were unavailable, so that we could not write an exhaustive and scholarly review in the available time. We hope that the report will focus attention, however, on major unsolved respiratory problems which require a significant additional investment of resources. If this is done, essential information leading to safer and greater diving capability should be acquired sooner than would otherwise be the case.

II. REVIEW OF COMPLETED INVESTIGATIONS

A. Control of Breathing

Information about the control of breathing in a hyperbaric environment is principally gathered from two sources: estimates of ventilatory responses to hypoxia, hypercapnia, and exercise; and estimates of arterial P_{CO_2}(Pa_{CO_2}).

Ventilatory response to CO_2 is reduced at depths. The most prominent of several mechanisms responsible for this effect seems to be the increased work of breathing dense gas (5,17,18,42,50). The response to CO_2 during ventilation with neon and N_2 was similar at depth, despite their different narcotic potencies, which suggests that inert gas narcosis is a much less prominent cause of the reduced ventilatory response to CO_2 than increased gas density (42). For a given Pa_{CO_2} during hyperbaric exposure, the output to respiratory muscles is constant (50). With increased gas density more inspiratory muscular power is required to overcome airway resistance to breathing, and less ventilation ensues. Recent studies suggest that output to the respiratory muscles may be greater at depth and during dense gas breathing, accounting for a lesser reduction in ventilation (6,41). Ventilatory response to hypoxia is not reduced during breathing of dense gases (8). Moderate elevation of Pa_{CO_2}

correlating with ambient pressure to 8.5 ATA has been observed (30,32). In view of these findings, depression of the respiratory control system by increased ambient pressure needs to be considered.

Although hypoventilation is a potential hazard, recent measurements at great depths have indicated that in resting conditions, arterial P_{CO2} is not elevated (28,36, Appendix B). These studies indicate that in these conditions no more than subtle changes in control of respiration occurred. At increased levels of exercise in dry hyperbaric chambers at depth, alveolar hypoventilation has been observed (4,19,33,49). This is almost certainly due to the increased work of breathing, and the degree of hypoventilation seems to be determined by the combined increase of the respiratory work load due to greater inspired gas density and the added external resistance to breathing. Again, barometric effects also need to be considered.

These changes must also be considered in light of the frequent observation that divers have a reduced ventilatory response to CO_2 (5, 19). Two additional observations have been made in recent deep dives: chamber subjects have an increased awareness of breathing, and during exercise in water severe choking dyspnea was noted in the absence of alveolar hypoventilation (36).

B. Pulmonary Mechanics

Most studies related to respiration at depth have examined some aspect of forced vital capacity (FVC). From these studies, some information concerning pulmonary statics is obtained, often indirectly. Vital capacity and its subdivisions, inspiratory capacity and expiratory reserve volume, either do not change or decrease slightly at great depth and gas density (9). Greater changes in these volumes were observed following rapid compression, with return to normal during acclimatization at depth (9,34). No pertinent measurements of functional residual capacity (FRC) are available. This limits the interpretation of pulmonary compliance measurements and static recoil pressures at various fractions of vital capacity. Given this limitation, these values do not change with depth or gas density in dry chambers (13,16,23,25,44). Dynamic compliance decreased approximately 50% during immersion in the prone and erect positions (37). This change was attributed to one or a combination of the following: pulmonary congestion, negative airway pressure, and craniad displacement of abdominal contents.

The vertical distribution of regional FRC was not affected by quiet breathing of sulfur hexafluoride, a gas four times more dense than air at 1 and 2 ATA. At higher flow rates, the regional distribution of ventilation and frequency dependence of compliance was different when breathing air as compared to sulfur hexafluoride (3,13,51). These findings indicated that the intrapulmonary distribution of ventilation is altered by breathing gas of increased density.

Airway resistance increases with gas density, causing a drop in maximal inspiratory and expiratory flow rates and in maximal voluntary ventilation (MVV) (2,22,26,44,46,47,48,52). The relationship is such that each of these measurements is inversely related to the density of inspired gas elevated to an exponential power between .4 or .5. One can therefore predict with reasonable accuracy any of these variables by dividing the surface value by the square root of inspired gas density at the selected depth.

To the extent that maximal exercise at depth is limited by maximal voluntary ventilation, maximal exercise at a given gas density can be predicted from the MVV and exercise ventilation measured at sea level. Observed levels of exercise ventilation during maximal tolerated exercise at depth generally agree with this prediction (4,22,36,47,52).

Some evidence for mechanical adaptation to depth was observed (36). Vital capacity, maximal voluntary ventilation, and maximal inspiratory flow increased in two subjects after 60 days of continuous exposure to 2 ATA of normoxic nitrogen (11). The mechanism of adaptation is not clear, but seems consistent with the effects of prolonged exercise of the respiratory musculature (21). Also, studies have shown an increase in maximal voluntary ventilation following deep dives compared to studies before the dive (36). One abundantly confirmed mechanism of adaptation is the increase in tidal volume and decrease in respiration rate associated with minimizing respiratory work when breathing dense gases (4,15).

Means of evaluating the resistance of external breathing assemblies and in particular underwater breathing gear have been described (38). One useful method consists of measuring the maximal voluntary ventilation while respiring through the breathing gear at a series of depths, and comparing these results to tests without breathing gear (27).

C. Gas Exchange

In dry chamber studies where ventilation is unimpeded by breathing apparatus resistance, adequate oxygenation of arterial blood in man has been demonstrated to depths of 1600 feet (49 ATA) (28,36, Appendix B). The alveolar-arterial gas pressure difference ($AaDO_2$) was appropriate for inspired gas conditions at 31 ATA (1000 ft) and studies of immersed divers to 1000 fsw indicate that gas exchange is similar to that observed in dry chamber studies when the breathing apparatus is optimal (12,36).

In one series of experiments, gross neurologic impairment was observed in goats exposed to multiple simulated depths extending to 152 ATA (5000 fsw) (7,20). These changes were first evident at approximately 49 ATA of helium/O_2 (1600 fsw). A small increase of the inspired oxygen tension reversed this neurologic impairment. This sequence of impairment and subsequent reversal with increased inspired tensions of O_2, at increasing depths, could be reproduced multiple times in one experimental diving exposure. The inference that the respiratory environment, characterized by a very dense breathing gas containing a small oxygen fraction, impeded diffusive transfer of O_2 from lung gas to blood, has not been supported by subsequent experiments. At a comparable depth of 49 ATA (1600 ft, helium/oxygen) no impairment of arterial blood gases was noted in humans (36). Unchanged normal values for $AaDO_2$ were noted in resting men exposed to varied densities of breathing gas, ranging from 0.3 to approximately 8.0 gm/liter, at depths ranging from one to 8.5 ATA (30). In anesthetized dogs breathing sulfur hexafluoride O_2 at 4 ATA no impairment of gas exchange was noted despite a breathing gas density equivalent to that of helium O_2 at 150 ATA (20 gm/liter) (24).

Increases in O_2 consumption ($\dot{V}O_2$) and CO_2 elimination ($\dot{V}CO_2$), and minute ventilation ($\dot{V}_E$), at increasing depths, were related to convective heat loss in a dense helium gas environment (30). A similar relationship was noted in the absence of increased pressure in subjects swimming in cold water (17). Part of the increase in oxygen uptake is also due to the increased work of breathing (14). Switching from air at 1 ATA to 100% O_2 at 2 ATA was associated with an increase in $\dot{V}O_2$ at the same level of exercise (31), but switching from air at 1 ATA to air at 2 ATA did not have the same effect (40). This is hard to reconcile with another experiment, in which $\dot{V}O_{2max}$ was found to increase by 9% when breathing air at 1.4 ATA (10).

D. Performance

Men have made experimental dry chamber dives to depths slightly in excess of 2000 fsw (61.6 ATA) (1). The capability to perform heavy work in the dry chamber has been demonstrated to 37 ATA (1200 fsw) (42). In the water light work has been performed successfully at 49 ATA (1600 fsw) (36). Exercise studies utilizing an optimal breathing circuit in chambers during immersion at depths as great as 1000 fsw (31 ATA) demonstrated exercise capabilities equal to those under comparable circumstances in a dry chamber (12,36). These findings seem to indicate that the capacity for performing work will be unimpaired by immersion if ventilation is not impeded significantly by underwater breathing apparatus.

Practical constraints prevent the design of underwater breathing apparatus (UBA) with optimal dynamic characteristics. Characteristics of underwater breathing apparatus which affect performance have been assessed; recent reviews outline methods of assessment and propose standards (29,38).

The need for better diver selection, to reduce morbidity and death, is generally accepted. Respiratory parameters are an obviously important element, insofar as limits to pulmonary function affect ventilation, gas exchange, and performance. Relatively few studies have focused on this problem systematically (43).

III. RECOMMENDATIONS

A. Introduction

In writing this report, the committee kept a particular goal in mind; this goal was used as a device for assessing what relevant respiratory knowledge was available and what was yet to be acquired. The projected goal was the safe and functionally useful exposure of man to depths ranging from just below the surface to 5000 fsw (152 ATA). In the course of this discussion certain general observations could be made.

Within the past decade, much information about gas exchange has been acquired. No serious limiting problems have been identified at the depths to which man has been exposed to date; in the absence of new developments, gas exchange should be unimpaired at 150 ATA. Maximum ventilation, though reduced by the effects of increased respired gas density, should also be adequate at the maximum projected depth. There would be an advantage in selecting subjects with very high sea-level MVV values, however, since they would attain their anticipated breathing limits at higher levels of work. In a similar vein, conditioning seems likely to enhance performance at maximal depth by delaying the occurrence of increased ventilation associated with anerobic metabolism during sustained work. Finally, available data do not reveal serious depression of ventilation if external burdens upon respiration are minimal.

In the general discussion of this model many important gaps in knowledge were identified. These problems are related to the general model in subsequent paragraphs. The panel believes that successful solution of these problems should help greatly in achieving the national goals of safer and more efficient diving.

B. Performance in the Water

Though many experiments have demonstrated no serious respiratory limitations for man at rest or doing light work during dry chamber experiments at simulated depths approaching 2000 fsw (62 ATA), there is a very large information gap concerning human underwater performance. Data at great depths in water are particularly limited; the current record in the open sea is 1148 fsw. Though a small number of careful studies on immersed man during experimental exposures as deep as 31 ATA (1000 fsw) have revealed no significant deviations from dry chamber measurements of gas exchange, ventilation, and performance, we do not know how to make good quantitative predictions about the design of underwater breathing apparatus and the selection of personnel. Therefore, a high priority should be assigned to research that will provide valid predictive information. The following recommendations, if implemented, will help in developing safer and more efficient operational competence in water to depths already attained in dry chamber experiments.

1. A symposium designed to summarize accumulated knowledge in the field should be planned. Both open literature and technical reports should be included in the bibliography of the scientific document which such a symposium would produce. The symposium participants could also make recommendations for future investigations.

2. Multivariable dose-response matrix research studies of underwater breathing apparatus, men, depth, and breathing gases during immersion should be encouraged. To develop valid concepts and mathematical statements that can be applied to equipment design, personnel selection, and operational planning, it will be necessary to study ventilatory characteristics under diverse test conditions, since the particular level of ventilation largely determines whether gas exchange will be adequate.

3. This review has helped the panel to appreciate more clearly some significant gaps in our understanding of respiration at depths. These gaps should be given priority in the planning of future research. Alveolar hypoventilation is a common and serious problem with potentially lethal consequences. Previous studies have identified multiple causative factors, including increased density of breathing gas, high-resistance underwater breathing apparatus, and the depressed ventilatory CO_2 response which divers acquire. Recently, alveolar hypoventilation secondary to moderate increases in ambient barometric pressure alone has been reported. Contributions by narcotic pressures of inert gas or high O_2 tensions may be significant. During operational diving, some or all of these factors are present simultaneously. How ventilatory control is affected by these interactions is unknown. This panel strongly recommends systematic investigation of the manner in which the above factors affect ventilatory control under diving conditions. The knowledge gained from such a study should help in developing guidelines for equipment design and operational procedures that will protect life and increase efficiency.

C. Effects of Hydrostatic Pressure

Investigations to determine the depth (hydrostatic) limits of the mammalian respiratory system should be encouraged. No data indicating whether respiratory problems will interfere with the safe and efficient exposure of man to pressures greater than 49-61 ATA (1600-2000 fsw) presently exist. Despite experimental evidence documenting adequate gas exchange and ventilation when breathing gases with densities appropriate to depth exposures of 150 ATA (5000 fsw), mammals exposed to hydrostatic pressures of this magnitude suffer severe and, at times, irreversible damage. The contribution of the respiratory system to these adverse manifestations must be clarified before the depth limit for man can be extended safely.

Technology and knowledge are available to answer relevant questions. Each component of the respiratory system in animals should be studied during exposure to ambient pressures of up to 150 ATA (5000 fsw). These components include control of ventilation (will animals breathe spontaneously and appropriately at extreme depths?), gas exchange between the environment and arterial blood, and peripheral gas exchange both at the capillary-cell interface and within the cell. At these extreme depths, a major problem for investigators will be separating the effects of ambient hydrostatic pressures from the consequences of high concentrations of respired inert gases in tissues. A very useful experimental model for this purpose is the liquid-breathing animal, since liquid replaces the inert gas in the respired medium. A recent and excellent review of this specialized field has been made available; it appears in this report as Appendix A.

D. Tissue Respiration

High priority should be given to investigations at increased ambient pressures of peripheral respiration, i.e., respiratory gas exchange at capillary-cell interfaces and within cells. Only recently have good techniques for quantitative assessment become available. An appropriate and major research thrust during the next decade will be determining how peripheral respiration is affected by hyperbaric exposures. This committee recommends that a panel of experts be selected to review the small data base concerned with this research area, and then to make appropriate recommendations.*

E. Effects of Carbon Dioxide

In the foreseeable future some level of hypercapnia is likely during operational diving, because of the practical constraints imposed upon equipment design plus the requirement for dense breathing gases. At some high level of imposed external resistance and increased breathing gas density, the uninterrupted performance of work by a diver would lead to serious functional impairment due to carbon dioxide retention. Therefore, the panel recommends that a high priority be given to investigations of tolerated limits for hypercapnia under conditions encountered in operational diving. As is true for all studies that involve respiratory control, the modified ventilatory behavior of the diver, under test conditions, is an important variable.

---

*Specialists in this area of research include Dr. VanLiew at S.U.N.Y., Buffalo, Dr. Chance at the University of Pennsylvania, Dr. Jobsis or Dr. Hempel at Duke University Medical Center, and Dr. Gonzalez-Fernandez at the National Institutes of Health.

F. Pulmonary Mechanics

1. Statics

a. Despite many previous measurements of ventilatory flow and compliance under diverse conditions of increased ambient pressure and gas density, pertinent measurements of total thoracic gas volume are lacking. To understand limits for ventilation and to ascertain mechanisms of apparent adaptation, measurements of pressure volume curves under diverse conditions of increased ambient pressure and increased gas density are needed. From this additional information, it should be possible to make more valid predictions of ventilatory flow limits at increased ambient pressure. Recent observations of adaptation, with increased ventilatory performance after prolonged exposure to increased ambient pressures, can only be interpreted reliably if static lung volumes and the pressure volume curve are described accurately under similar environmental conditions.

b. Recent investigations have focused attention upon the role of the chest and abdominal wall structures in supporting ventilation. The interactions between the chest and abdominal wall are necessarily modified by immersion. Depth, dense gases, and external resistance to breathing imposed by underwater breathing apparatus are additional variables that may modify physiologic behavior of the thoracoabdominal structures. Understanding of these interrelationships is particularly important because operational diving imposes burdens on the ventilatory apparatus that lead to hypoventilation. Therefore, support for investigations to describe and quantitate the role of the chest wall and abdominal diaphragmatic structures as modified by conditions encountered in diving is recommended.

2. Dynamics

a. Little information is available concerning the homogeneity of inspired gas distribution under conditions encountered in diving. Accordingly, support of the investigations evaluating this aspect of respiratory function is recommended. While inhomogeneity of inspired gas distribution has not adversely affected gas exchange in an overt manner, such changes, if present, may lead to long-term adverse modifications of respiration at sea level in exposed individuals.

b. Recent observations suggest that some ventilatory adaptation occurs after prolonged exposure to dense gases at depth. To the extent that the apparent recovery of ventilatory flow occurs, the mechanism for this favorable response becomes important theoretically and practically. Changes in lung volume, lung recoil, or upstream resistance may be involved. Investigations to evaluate the mechanisms and extent of enhanced flow after exposure to depth are therefore important. How these findings are related to the favorable effects of respiratory muscular conditioning upon maximal ventilation needs study as well.

G. Oxygen Consumption

There is little information about the cost of breathing dense gases at depth. Differences between VO_2 at depth compared to otherwise identical surface measurements have been assumed to reflect the increased oxygen cost of breathing. Since the depths projected for current and future human exposures require breathing of very dense gases which will impose significant metabolic expenditures, systematic investigation of incurred energy costs is recommended.

Unexplained discrepancies concerning the effects of increased ambient pressure and hyperoxis on oxygen consumption at maximal sustained exercise exist in the current literature. Conflicting but possibly related observations report increased oxygen consumption compared to sea-level air studies when breathing pure O_2 at 2 ATA; no increase in oxygen consumption at 2 ATA of air compared to sea-level air studies; and a significant increase in maximal oxygen consumption at 1.4 ATA of air compared to sea-level air studies. Clarification of these unexplained observations would improve our understanding of respiratory limits and help in the development of operational procedures that would enhance performance and safety.

H. Other

Since pulmonary metabolism, surface activity, and defense mechanisms preserve the ability of the lung to function, further information about these parameters at depth is needed. While measurements of dynamic compliance at simulated depth have revealed no striking changes from dry chamber experiments, the long-term effects of breathing gases upon lung distensibility are unknown. There is increasing evidence that gases previously regarded as inert do exert biologic effects. Therefore, an appropriate subject for investigation is how dynamic pulmonary function is affected by short and prolonged exposures to special breathing gases at increased ambient pressures.

The committee briefly discussed novel approaches to overcoming respiratory limits imposed on operational diving, including liquid breathing and gill breathing. It is not yet possible to assess the practical value of these approaches, but the committee recognizes that these investigations have contributed importantly to our understanding of respiration in areas relevant to diving.

IV. LABORATORIES INVOLVED IN RESPIRATION AND PULMONARY FUNCTION RESEARCH RELATED TO HYPERBARIC EXPOSURES

The committee was most reluctant to prepare the following list, because the assembled science information summaries were incomplete, and personal biases were introduced. Furthermore, the laboratory capabilities for supporting investigations can change dramatically in a short period of time, with loss of funding or key personnel. Agencies receiving this report should recognize these limitations and seek out the large number of interested investigators who are capable of making major contributions who are located in laboratories not included in this list.

U.S. Laboratories with Technologic and Professional Capabilities for Performing Human Hyperbaric Respiratory Studies

Colorado State University, Fort Collins, Colorado
8.6 Ata (250 fsw)), dry
Peter Hall

F. G. Hall Laboratory for Environmental Research, Duke University, Durham, N.C.
31 Ata (1000 fsw), saturation, wet
H. A. Saltzman, J. A. Kylstra, J. V. Salzano, J. Miller

Institute for Applied Physiology and Medicine, Seattle, Washington
10 Ata (300 fsw), dry
Merrill C. Spencer

Institute for Environmental Medicine, University of Pennsylvania, Philadelphia, Pa.
55.5 Ata (1800 fsw), saturation, wet
C. J. Lambertsen, J. Clark

Marine Biomedical Institute, University of Texas, Galveston, Texas
26 Ata (800 fsw), saturation, wet
Brian A. Hills

Navy Experimental Diving Unit, Panama City, Florida
69 Ata (2500 fsw), saturation, wet
W. H. Spaur

Naval Medical Research Institute, Bethesda, Maryland
101 Ata (3300 fsw), saturation to 2200 fsw, wet (due 1978)
Mark Bradley, J. Vorosmarti

Naval Submarine Medical Research Laboratory, Groton, Connecticut
10 Ata (300 fsw), saturation, dry
Claude Harvey, Karl Schaefer

St. Luke's Hospital, Milwaukee, Wisconsin
7.8 Ata (224 fsw), dry
Eric P. Kindwall

SUNY at Buffalo, New York
155 Ata (5000 fsw), wet
H. Rahn, L. Farhi

Taylor Diving and Salvage Co., Belle Chasse, Louisiana
61 Ata (2000 fsw), saturation, wet
Peter Erickson

Tarrytown Labs., Ltd., Tarrytown, N.Y.
18.4 Ata (675 fsw), saturation, dry
R. W. Hamilton

University of Southern California at Avalon, California
7.8 Ata (225 fsw), dry
Andrew J. Pilmanis

U.S. Navy Submarine Development Group One, San Diego, California
Mark II Deep Diving System, 31 Ata (1000 fsw) on ELK RIVER, IX 501
Paul Linaweaver

USAF School of Aerospace Medicine, San Antonio, Texas
7 Ata (200 fsw), dry
Jefferson C. Davis

Westinghouse Ocean Research and Engineering Center, Annapolis, Maryland
46 Ata (1500 fsw), saturation, wet
W. J. O'Neill

REFERENCES

1. Agarate, C. A., and A. J. Jegou. 1973. A simulated dive at 2001 feet. In: Preprints Offshore Technology Conference (Houston, Texas). Vol. I., p. 511-513.
2. Anthonisen, N. R., M. E. Bradley, J. Vorosmarti, and P. G. Linaweaver. 1971. Mechanics of breathing with helium-oxygen and neon-oxygen mixtures in deep saturation diving. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. New York: Academic.
3. Baker, B., B. Murphy, P. T. Macklem, and J. Milic-Emili. 1974. Effects of inspiratory flow rates on the regional distribution of inspired gas. J. Appl. Physiol. 37:8-17.
4. Bradley, M. E., N. R. Anthonisen, J. Vorosmarti, and P. G. Linaweaver. 1971. Respiratory and cardiac responses to exercise in subjects breathing helium-oxygen mixtures at pressures from sea level to 19.2 atmospheres. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. New York: Academic.
5. Broussolle, B., P. Varene, E. Bensimon, and J. L'Huillier. 1969. La pression partielle alveolaire du CO_2 au cours du travail musculaire a 1.4 et 7 atmospheres absolues. (Alveolar CO_2 partial pressure during muscular activity at 1.4 and 7 atmospheres absolute.) Bull. Medsubhyp. 1:15-16.
6. Camporesi, E., J. F. Salzano, and H. A. Saltzman. Effects of hydrostatic pressure and gas density on regulatory mechanisms of respiration and circulation. Unpublished observations. F. G. Hall Laboratory, Duke University Medical Center.
7. Chouteau, J., J.-Y. Cousteau, J. Alinat, and C. F. Aquadro. 1968. Sur les limites physiologiques de la plongee a saturation a l'air et aux melanges syntetiques (O_2-N_2, O_2-He). (The physiological limits of diving with air saturation and with synthetic mixtures (O_2-N_2, O_2-He)). Rev. Physiol. Subaquatique Med. Hyperbare 1:38-44. (Trans. NavShips 1272, Mar. 1971.)
8. Doell, D., M. Zutter,and N. R. Anthonisen. 1973. Ventilatory responses to hypercapnia and hypoxia at 1 and 4 ATA. Respiration Physiol. 18:338-346.
9. Dougherty, J. H., Jr., and K. E. Schaefer. 1969. The effect on pulmonary functions of rapid compression in saturation-excursion dives to 1,000 ft. U.S. Nav. Submar. Med. Cent., Rept. SMRL 573.
10. Fagraeus, L., J. Karlsson, D. Linnarsson, and B. Saltin. 1973. Oxygen uptake during maximal work at lowered and raised ambient air pressures. Acta Physiol. Scand. 87:411-421.
11. Fisher, A. B., A. B. Dubois, R. W. Hyde, C. J. Knight, and C. J. Lambertsen. 1970. Effect of two months' undersea exposure to N_2O_2 at 2.2 Ata on lung function. J. Appl. Physiol. 28:70-74.
12. Flynn, S. T., H. A. Saltzman, and J. K. Summitt. 1972. Effects of head-out immersion at 19.18 Ata on pulmonary gas exchange in man. J. Appl. Physiol. 33:113-119.

13. Forkert, L., L. D. H. Wood, and R. M. Cherniack. The effect of gas density on dynamic pulmonary compliance. J. Appl. Physiol. 39:906-910.
14. Glauser, S. C., E. M. Glauser, and B. F. Rusy. 1967. Gas density and the work of breathing. Respiration Physiol. 2:344-350.
15. Hesser, C. M., and B. Holmgren. 1959. Effects of raised barometric pressures on respiration in man. Acta Physiol. Scand. 47:28-43.
16. Hyacinthe, R., and R. Broussolle. 1972. Etude de la mecanique ventilatoire au cours d'une plongee fictive a 51 ATA en helium-oxygene. (Study of the ventilatory mechanics during a simulated dive at 51 ATA with helium-oxygen.) Bull. Medsubhyp. 8:4-6.
17. Kebkalo, V. I., and V. P. Ponomarev. 1971. Lung ventilation and gas exchange of a man breathing different gas mixtures while swimming under water. Fiziol. Zh. SSSR 57:1802-1807. (Trans. NASA-TT-F-14, 260, 1972.)
18. Lambertsen, C. J., R. Gelfand, M. J. Lever, G. Bodammer, N. Takano, T. A. Reed, J. G. Dickson, and P. T. Watson. 1973. Respiration and gas exchange during a 14-day continuous exposure to 5.2% O_2 in N_2 at pressure equivalent to 100 fsw (4 ata). Aerospace Med. 44:844-849.
19. Lanphier, E. H. 1963. Influence of increased ambient pressure upon alveolar ventilation. In: Proc. 2nd Symp. Underwater Physiol., edited by C. J. Lambertsen, and L. J. Greenbaum, Jr. Washington, D. C.: National Academy of Sciences, National Research Council.
20. Lanphier, E. H. 1969. Pulmonary function. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. H. Elliott. London: Bailliere Tindall.
21. Leith, D. E., and M. Bradley. 1975. Ventilatory muscle strength and endurance training. Fed. Proc. 34:386.
22. Maio, D. A., and L. E. Fahri. 1967. Effect of gas density on mechanics of breathing. J. Appl. Physiol. 23:687-693.
23. Marshall, R., E. H. Lanphier, and A. B. DuBois. 1956. Resistance to breathing in normal subjects during simulated dives. J. Appl. Physiol. 9:5-10.
24. Martin, R. R., M. Zutter, and N. R. Anthonisen. 1972. Pulmonary gas exchange in dogs breathing SF_6 at 4 ATA. J. Appl. Physiol. 33:86-92.
25. Mead, J. 1956. Measurement of inertia of the lungs at increased ambient pressure. J. Appl. Physiol. 9:208-212.
26. Miller, J. N., O. D. Wangenstern, and E. H. Lanphier. 1971. Ventilatory limitations on exertion at depth. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. New York: Academic.
27. Morrison, J. B., and W. S. Butt. 1972. Effect of underwater breathing apparatus and absolute air pressure on divers' ventilatory capacity. Aerospace Med. 43:881-888.
28. Overfield, E. M., H. A. Saltzman, J. A. Kylstra, and J. V. Salzano. 1969. Respiratory gas exchange in normal men breathing 0.9 percent oxygen in helium at 31.3 Ata. J. Appl. Physiol. 27:471-475.

29. Reimers, S. 1974. Proposed standards for the evaluation of the breathing resistance of underwater breathing apparatus. U.S. Navy Exp. Diving Unit Rept. NEDU 19-73.

30. Saltzman, H. A., J. V. Salzano, G. D. Blenkarn, and J. A. Kylstra. 1971. Effects of pressure on ventilation and gas exchange in man. J. Appl. Physiol. 30:443-449.

31. Salzano, J. V., W. H. Bell, W. B. Weglicki, and H. A. Saltzman. 1967. Metabolic, respiratory and hemodynamic responses to exercise at increased oxygen pressure. In: Proc. 3rd Symp. Underwater Physiol., edited by C. J. Lambertsen. Baltimore: Williams and Wilkins.

32. Salzano, J. V., and D. Kerem. 1974. Hydrostatic pressure: Effects on arterial blood and cerebrospinal fluid acid-base parameters and electrolytes. Undersea Biomed. Res. 1:A25.

33. Salzano, J., D. C. Rausch, and H. A. Saltzman. 1970. Cardiorespiratory responses to exercise at a simulated seawater depth of 1,000 feet. J. Appl. Physiol. 28:34-44.

34. Schaefer, K. E., C. R. Carey, and J. H. Dougherty, Jr. 1971. Pulmonary function and respiratory gas exchange during saturation-excursion diving to pressures equivalent to 1000 feet of sea water. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. New York: Academic.

35. Shikanov, Y. P. 1973. Spravochnik vodolaza. (Diver's handbook.) Moscow: Izd-vo Vozenizdat.

36. Spaur, W. H. 1974. 1600 foot dive. In: The Working Diver. Washington, D. C.; Marine Technology Society.

37. Sterk, W. 1971. Effect of SCUBA diving on pulmonary compliance. In: Abstracts of the Twenty-fifth Congress of Physiological Sciences Satellite Symposium. Recent progress in fundamental physiology of Diving, Marseille, France, p. 27-28. (Proceedings unpublished)

38. Sterk, W. 1973. Respiratory Mechanics of Divers and Diving Apparatus. Utrecht, Netherlands: Drukkerij Elinkwijk.

39. Strickland, C. L., and R. L. Hittleman. 1972. Analysis of three lighting sources. Offshore 32:72,75-76,79.

40. Telfer, A. B. M., and S. M. Jennett. 1965. Ventilation and oxygen uptake during exercise at high pressure. In: Hyperbaric Oxygenation, edited by I. McA. Ledingham. Edinburgh: E. and S. Livingstone.

41. Troshikin, G. V. 1971. Respiration in an atmosphere under high pressure. Fiziol. Zh. SSSR 57:1808-1812.

42. University of Pennsylvania, Institute for Environmental Medicine. 1972. Predictive Studies III. Effects of respiratory gases at extreme pressures: simulation of respiratory function and density influences to 2,000, 3,000, 4,000 and 5,000 feet of sea water.

43. Vail, E. Naval Coastal Systems Laboratory. Panama City, Florida.

44. Verene, P., and C. Jacquemier. 1969. La mecanique ventilatoire en plongee profonde. (Deep diving ventilatory mechanism.) Rev. Physiol. Subaquatique Med. Hyperbare 1:271-275.

45. Varene, P., G. Saumon, H. Vieillefond, and J. L'Huillier. 1971. Mecanique ventilatoire en plongee profonde. Resultats de

l'experience Physalie V. (Ventilatory mechanics in deep diving. Results of the Physalie V experiment.) Bull. Medsubhyp. 6:9-16.

46. Varene, P., J. Timbal, C. Jacquemier. 1967. Effect of different ambient pressures on airway resistance. J. Appl. Physiol. 22:699-706.

47. Wood, L. D. H., and A. C. Bryan. 1971. Mechanical limitations of exercise ventilation at increased ambient pressure. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. New York: Academic.

48. Wood, L. D. H., and A. C. Bryan. 1969. Effect of increased ambient pressure on flow-volume curve of the lung. J. Appl. Physiol. 27:4-8.

49. Wood, L. D. H., and A. C. Bryan. (in press). Exercise ventilatory mechanics at increased ambient pressure. J. Appl. Physiol.

50. Wood, L. D. H., and A. C. Bryan. 1970. Respiratory sensitivity to CO_2 at increased ambient pressure. Physiologist 13:348.

51. Wood, L. D. H., F. Ruff, A. C. Bryan, and J. Milic-Emili. 1969. Influence of air density on the distribution of ventilation. Physiologist 12:398.

52. Wood, W. B., L. H. Leve, and R. D. Workman. 1962. Ventilatory dynamics under hyperbaric states. U.S. Navy Exp. Diving Unit Res. Rept. 1-62.

Appendix A

LIQUID BREATHING

A Panel Review*

Hermann Rahn, Ph.D., Chairman	State University of New York at Buffalo
Robert W. Hamilton, Jr., Ph.D.	Ocean Systems, Inc., Tarrytown, New York
Johannes A. Kylstra, M.D.	Duke University School of Medicine
Claude Lenfant, M.D.	National Heart and Lung Institute, N.I.H.
Leonard M. Libber, Ph.D.	Office of Naval Research, Department of Physiology, Lund, Sweden
Jerome H. Modell, M.D.	University of Florida College of Medicine
Donald J. Sass, M.D.	Naval Medical Research Institute, National Naval Medical Center
Heinz R. Schreiner, Ph.D.	Union Carbide Corporation, Tarrytown, New York

*This panel convened in Washington, D.C., on January 25 and 26, 1974, under the sponsorship of Wheeler Industries, Inc., for a review and critical evaluation of the current status, problems, and prospects of liquid breathing research.

This appendix has been reviewed and is endorsed with enthusiasm by the subcommittee which prepared Part 4 of the National Plan for the Safety and Health of Divers. This appendix does not necessarily reflect the views of the Undersea Medical Society Inc., or expert authors working on other portions of the National Plan, however.

Early History

One of the hazards of diving is the presence of gas in the lungs which in order to permit ventilation and prevent lung damage has to be at a pressure which is equal to the pressure exerted on the chest by the surrounding water. Pressure forces gases into solution in the blood and, regardless of the gas mixture used, the metabolically inert "filler" gas dissolved in excessive amounts in blood and tissues may be released as bubbles whenever a diver returns to the surface after a deep dive, producing decompression sickness. Theoretically, decompression sickness could be avoided by either having the diver breathe a gas mixture of which the inert fraction does not dissolve in blood at all, or by filling his lungs with a liquid. Since there is no gas known which is completely insoluble in water, the replacement of inert gas in the breathing mixture by a liquid would seem the only way to eliminate the hazards of decompression sickness and avoid the need for long periods of decompression during ascent to the surface after a deep dive.

The idea of having divers breathe an oxygenated liquid instead of a gas mixture may have occurred first to Stein and Sonnenschein (1950), who wrote:

> "Water with oxygen dissolved under pressure and properly adjusted for osmotic, ionic, and density characteristics, et cetera, conceivably may sustain life when it surrounds the man and fills his lungs. The other components and adjustments necessary are still unknown, except that carbon dioxide will have to be removed chemically. There is no reason why, with water as a diluent for oxygen, man may not be able to work safely at any depth to which a fish may go..."

The first experimental evidence which seemed to support these contentions was published twelve years later. Mice were reported to stay alive for hours while submerged in salt solutions equilibrated with oxygen at high pressure (Kylstra 1962a, 1962b; Goodlin 1962). The animals appeared to inhale and exhale the salt solution, responded to external stimuli when not previously anesthetized, and were obviously capable of extracting adequate amounts of dissolved oxygen from their aqueous environment. Mice submerged in a hyperbarically oxygenated balanced salt solution to which a carbon dioxide buffer, THAM (Trishydroxymethyl aminomethane), had been added lived markedly longer than in an identical but unbuffered salt solution (suggesting that carbon dioxide elimination was deficient in these saline breathing animals) and they continued making respiratory movements for long periods of time even when subjected to pressures up to 160 atmospheres, i.e., a pressure existing in the oceans at a depth of approximately one mile (Kylstra, Tissing, and van der Maen 1962).

Additional information provided during the ensuing twelve years by several investigators working at different laboratories has now made it possible to delineate more clearly the promises and problems of the liquid breathing concept.

What is Firmly Established

Anesthetized normothermic dogs can breathe an oxygenated salt solution for one hour (Kylstra, Paganelli and Lanphier 1966) or oxygenated liquid fluorocarbon for up to eight hours (Modell, Newby and Ruiz 1970; Modell, Hood, Kuck and Ruiz 1971; Saga, Modell, Calderwood, Lucas, Tham and Swenson 1973; Tuazon, Modell, Hood and Swenson 1973), resume spontaneous breathing of room air and survive.

Some saline breathing dogs have survived without any obvious impairment for a period of ten years (Kylstra, personal communication). After breathing liquid fluorocarbon for one hour dogs have survived for at least eighteen months (Modell et al. 1971) (FX-80, electively sacrificed), for at least 23 months (Modell, Tham, Modell, Calderwood and Ruiz 1973; Tuazon et al. 1973) (Caroxin-D, electively sacrificed), and for at least 27 months (Saga et al. 1973) (Caroxin-F, still alive, January 1974), without any apparent ill effects. Complete pulmonary function tests showed no abnormalities 72 hours after ventilation with liquid fluorocarbon (Caroxin-F) for one hour (Saga et al. 1973). These animals were followed with serial pulmonary function tests, also normal, for one year.

Dogs which have been ventilated with fluorocarbons have subsequently conceived and sired apparently normal offspring (Modell, personal communication). One dog, pregnant at the time of ventilation with hyperbarically oxygenated saline, subsequently delivered nine healthy pups (Kylstra et al. 1966).

Three laboratories have demonstrated that fluorocarbon liquid breathing mice can be decompressed from pressures of 33 (Collan and Clark 1967), 100 (Kylstra, Nantz, Crowe, Wagner and Saltzman 1967), and 250 (Lundgren and Ornhagen 1975, Ornhagen 1971) atmospheres to one atmosphere within seconds. Most of these animals survived.

The lungs of anesthetized man, one at a time, can be completely filled and ventilated with an isotonic salt solution without lasting demonstrable function impairment (Kylstra, Rausch, Hall and Spock 1971). In patients with alveolar proteinosis, cystic fibrosis of the pancreas, bronchiectasis, intractable asthma, and accidental inhalation of radioactive dust, such therapeutic unilateral lung lavage with isotonic saline has been beneficial. The patients did not complain of unpleasant sensations resulting from the presence of a saline residue remaining in the lung for 24 hours after the lavage (Kylstra 1974, personal communication). A conscious man (whose trachea and larynx had been topically anesthetized to facilitate intubation, but who otherwise received no medication) has tolerated the filling of one lung with saline as well as the flow of saline in and out of the lung (Kylstra 1968).

During transverse acceleration, air breathing dogs develop arterial hypoxemia due to dependent pulmonary arteriovenous shunting, but when the same dogs are ventilated with liquid fluorocarbon, arterial hypoxemia and downward displacement of the heart are prevented (Sass, Ritman, Caskey, Banchero and Wood 1972).

When dogs breathe oxygenated liquids with densities greater than blood, the pulmonary blood flow is shifted toward the uppermost region of the lung. When dogs breathe liquid with densities less than 1.0 (silicone oil, density 0.8), a shift of blood flow toward the dependent region of the lung is seen (Sass, Wood, Greenleaf, Ritman and Smith 1972).

Adequate (at least 80 Torr) arterial oxygen tensions can be maintained in anesthetized, normothermic dogs for at least eight hours while ventilated with oxygenaged fluorocarbon liquid at 1 ATA (Modell et al. 1970; Modell et al. 1971; Saga et al. 1973; Sass et al. 1972; Tuazon et al. 1973), or for one hour in hyperbarically oxygenated saline at 5 ATA (Kylstra et al. 1966).

Both lungs of primates (stub-tailed monkeys) have been ventilated simultaneously with oxygenated fluorocarbon (Caroxin-D). Each monkey was so ventilated on at least two separate occasions. The monkeys survived (Modell, Calderwood and Ruiz, personal communication).

All mammals ventilated with liquid and reported to have survived 36 hours or longer have developed arterial CO_2 tensions greater than 40 Torr during the episode of liquid breathing (Calderwood, Modell, Rogow, Tham and Hood 1973; Kylstra et al. 1966; Gollan and Clark 1967). After resumption of gas breathing, CO_2 tension returned to normal within fifteen minutes (Modell et al. 1970; Modell et al. 1971; Saga et al. 1973; Tuazon et al. 1973).

Experimental evidence in dogs suggests that the minute volume of saline ventilation is severely limited and under optimal conditions may not exceed approximately 6 liters per minute (Schoenfisch and Kylstra 1973). However, dogs mechanically ventilated with oxygenated FCSO liquid fluorocarbon in a whole-body water immersion respirator maintained normal P_{aCO2} for 4-8 hours (Sass et al. 1972).

Expiratory flow rates of saline from one lung, measured in patients, suggest that 6 liters per minute may also be the limit for ventilation with liquid in man (Kylstra 1974, personal communication). Minute ventilation with fluorocarbons should be similarly limited.

Very small amounts of fluorocarbon can be detected in arterial or venous blood within minutes of ventilating the lungs with fluorocarbon (Holaday, Fiserova-Bergerova and Modell 1972; Sass, Van Dyke, Wood, Johnson and Didisheim, personal communication). Fluorocarbon can be found in all major tissues for at least one year after breathing Caroxin-F and D. The concentration measured in the liver was .004 mg/gm tissue, whereas the concentration in the lung is approximately 1 mg/gm (Saga et al. 1973). No adverse effects of these retentions have been observed to date.

Serial biopsies of lung tissues show an exponential decrease of fluorocarbon concentrations with some residual remaining 24 months after breathing Caroxin-F (Modell, personal communication).

Serum concentrations of Na, Cl, Ca, Mg, and K are maintained at normal levels during and after ventilation with fluorocarbon liquids for up to eight hours (Calderwood et al. 1973; Modell et al. 1970; Sass et al. 1972). No appreciable changes in body weight were observed after saline ventilation up to one hour (Kylstra et al. 1966).

No appreciable changes in serum electrolyte concentration have been observed following therapeutic lung lavage with up to 40 liters of saline in man (Kylstra 1974, personal communication).

Fluorocarbon breathing has been demonstrated to wash aqueous material from the lungs of dogs (Calderwood, Modell, Ruiz, Brogdon and Hood 1973).

All the results with fluorocarbons were obtained with liquids not specifically designed for liquid breathing.

What Remains to be Investigated or Developed

New improved liquids (aqueous, non-aqueous, or mixtures of these) need to be developed and tested. When ventilating both lungs simultaneously with these liquids, they should provide:

a) Normal oxygenation

b) Normal Pa_{CO2}

c) Complete disappearance from the animal within a reasonable period of time

d) Absence of toxicity

e) A high solubility for O_2 and CO_2, a low density, and a low vapor pressure as well as ease of removal from the lung for rapid restoration of spontaneous air breathing.

Knowledge of the physical characteristics of these fluids, such as density, viscosity, surface tension, vapor pressure, thermal conductivity, heat capacity, diffusion coefficients for oxygen and carbon dioxide, and solubility in body tissues and fluids is important.

Bilateral simultaneous lung lavage in animal models of diseases to facilitate therapeutic lung lavage in infants and children.

The mechanism of formation of gas embolism following the intravenous injection of some fluorocarbon liquids.

Pressure equilibration of all gas containing cavities of the body during liquid breathing under increased ambient pressure, with particular attention to sinuses, middle ear, and mastoid cavities.

Communication, speech, and hearing during liquid breathing.

The integrity and turnover rate of lung surfactants during and following liquid breathing.

Methods for ventilatory assist to achieve optimal liquid ventilation without trauma and also provide for proper heat exchange.

The possible cumulative effects of liquid breathing to determine how frequently it can safely be repeated.

The physiological limits of hydrostatic pressure tolerance in liquid breathing animals. Liquid breathing provides a unique research tool for assessing man's tolerance to high hydrostatic pressures, and thus for delineating the depths which a free-swimming diver might ultimately attain.

Oxygen toxicity. At present there is no published evidence of oxygen toxicity in animals subjected to liquid breathing under high pressure, but further investigations are clearly indicated.

Priority Investigations

Priorities of other topics will depend upon the specific goals of possible applications. Of the highest priority are investigations directed at the development and testing of improved liquids and the further development of ventilatory-assist devices.

REFERENCES, Appendix A

Calderwood, H. W., J. H. Modell, L. Rogow, M. K. Tham, and C. I. Hood. 1973. Morphologic and biochemical changes in dogs after ventilation with Caroxin-D fluorocarbon. Anesthesiology 39:488-495.

Calderwood, H. W., J. H. Modell, B. C. Ruiz, J. E. Brogdon, and C. I. Hood. 1973. Pulmonary lavage with liquid fluorocarbon in a model of pulmonary edema. Anesthesiology 38:141-144, 1973.

Gollan, F., and L. C. Clark. 1967. Prevention of bends by breathing an organic liquid. Trans. Assoc. Am. Physicians 29:102-109.

Goodlin, R. 1962. Fetal incubator. Lancet 1:1356.

Holaday, D. A., V. Fiserova-Bergerova, and J. H. Modell. 1972. Uptake, distribution, and excretion of fluorocarbon FX-80 (Perfluorobutyl Perfluorotetrahydrofuran) during liquid breathing in the dog. Anesthesiology 37:387-394.

Kylstra, J. A. 1962a. Breathing fluid. Experientia 18:68.

Kylstra, J. A. 1962b. Drowning: the role of salts in the drowning fluid. Acta Physiol. Pharmacol. Neerl. 10:327-334.

Kylstra, J. A., M. O. Tissing, and A. van der Maen. 1962. Of mice as fish. Trans. Am. Soc. Artif. Int. Organs 8:378-383.

Kylstra, J. A., C. V. Paganelli, and E. H. Lanphier. 1966. Pulmonary gas exchange in dogs ventilated with hyperbarically oxygenated liquid. J. Appl. Physiol. 21:177-184.

Kylstra, J. A., R. Nantz, J. Crowe, W. Wagner, and H. A. Saltzman. 1967. Hydraulic compression of mice to 166 atmospheres. Science 158:793-794.

Kylstra, J. A. 1968. Experiments in water breathing. Sci. Am. 219: 66-74.

Kylstra, J. A., D. C. Rausch, K. D. Hall, and A. Spock. 1971. Volume-controlled lung lavage in the treatment of asthma, bronchiectasis, and mucoviscidosis. Am. Rev. Respirat. Diseases 103:651-665.

Lundgren, C. E. G., and H. Ch. Ornhagen. (in press) Hydrostatic pressure tolerance in liquid breathing mice. In: Proc. 5th Symp. Underwater Physiol., edited by C. J. Lambertsen.

Ornhagen, H. Ch. 1971. Liquid breathing. 16-mm silent color film. Laboratory of Aviation and Naval Physiology, University of Lund, Sweden.

Modell, J. H., E. J. Newby, and B. C. Ruiz. 1970. Long-term survival of dogs after breathing oxygenated fluorocarbon liquid. Fed. Proc. 29:1731-1738.

Modell, J. H., C. I. Hood, E. J. Kuck, and B. C. Ruiz. 1971. Oxygenation by ventilation with fluorocarbon liquid (FX-80). Anesthesiology 34:312-320.

Modell, J. G., M. K. Tham, J. H. Modell, H. W. Calderwood, and B. C. Ruiz. 1973. Distribution and retention of fluorocarbon in mice and dogs after injection or liquid ventilation. Toxicol. Appl. Pharmacol. 26:86-92.

Saga, S., J. H. Modell, H. W. Calderwood, A. J. Lucas, M. K. Tham, and E. W. Swenson. 1973. Pulmonary function after ventilation with fluorocarbon liquid P-12F (Caroxin-F). J. Appl. Physiol. 34:160-164.

Sass, D. J., E. L. Ritman, P. E. Caskey, N. Banchero, and E. H. Wood. 1972. Liquid breathing: prevention of pulmonary arterial-venous shunting during acceleration. J. Appl. Physiol. 32:451-455.

Sass, D. J., E. H. Wood, J. F. Greenleaf, E. L. Ritman, and H. C. Smith. 1972. Effects of breathing liquid fluorocarbons on regional differences in pleural pressures and other physiological parameters. Tech. Rept. SAM-TR-72-15, USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC), Brooks AFB, p. 1-173.

Schoenfisch, W. H., and J. A. Kylstra. 1973. Maximum expiratory flow and estimated CO_2 elimination in liquid ventilated dogs' lungs. J. Appl. Physiol. 35:117-121.

Stein, S. N., and R. R. Sonnenschein. 1950. Electrical activity and oxygen tensions of brain during hyperoxic convulsions. J. Aviation Med. 21:401-404.

Tuazon, J. G., J. H. Modell, C. I. Hood, and E. Swenson. 1973. Pulmonary function after ventilation with fluorocarbon liquid (Caroxin-D). Anesthesiology 38:134-140.

Appendix B

Supplemental Data Relevant to Reference 36

Simulated Depth		Dry (D) or Immersed (I)	PI_{O_2}	Pa_{O_2}	Pa_{CO_2}	pHa
Ata	fsw	Rest (R) or Exercise (E)	mmHg	mmHg	mmHg	
42	1378	DR (5 subjects)	252	187	38.0	7.47
37	1192	DR (6 subjects)	245	172	40.0	7.41
31	1000	DR (4 subjects)	266	172	36.0	7.42
49	1600	IR	*	329	32.0	7.47
49	1600	IE(1)	*	387	35.0	7.37
49	1600	IE(2)	*	402	21.5	7.40
49	1600	IR	*	303	35.0	7.45
49	1600	IE(1)	*	240	43.0	7.42
49	1600	IE(2)	*	240	42.0	7.43
49	1600	IR	*	240	36.0	7.44
49	1600	IE(1)	*	277	25.0	7.46
49	1600	IE(2)	*	227	45.0	7.35

*Immersed subjects at rest for 10 minutes wearing MK10 closed-circuit underwater breathing apparatus, which controlled inspired PO_2 above set point of 0.4 ATA (304 mmHg).

PSYCHOLOGICAL FACTORS INVOLVED IN UNDERSEA HYPERBARIC EXPOSURES

(Retitled - Selection and Training of Professional Divers)

Part #5 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Arthur J. Bachrach, Ph.D. (Co-Chairman)
Chairman, Behavioral Sciences Dept., NMRI
Bethesda, Maryland

James W. Miller, Ph.D. (Co-Chairman)
Deputy Director, Manned Undersea Science & Technology, NOAA
Rockville, Maryland

James Joiner
Executive Director, Commercial Diving Center
Wilmington, California

Ramsey Parks
Dept. Chairman, Marine Technology, Santa Barbara City College, Santa Barbara, California

James Stewart
Diving Officer, Scripps Institution of Oceanography
La Jolla, California

Harold Ginzburg, M.D. (Advisor)
Medical Director, Tarrytown Labs, Ltd.
Tarrytown, New York

TABLE OF CONTENTS and Organization for part 5

Selection and Training of Professional Divers

I. Basic Concepts in Selection and Training 1

A. Diver Selection

1. Age
2. Certified sport diver
3. Marital status
4. Education
5. Veteran status
6. Written tests
7. Medical examinations

B. Diver Training

1. Diver task analysis

a. Diving personnel

1) Systems diver
2) Diver
3) Diver/Tender

b. Tending personnel

1) Professional Tender
2) Tender

c. The panel's recommendation for classification

1) Supervisor
2) Life support specialist
3) Diver
4) Tender

C. Operational Model

D. Training Model

1. Skills already acquired
2. Basic knowledge
3. Advanced skill training

II. Major Sectors Involving Professional Divers 6

A. Industrial

B. University

C. Governmental

D. Civilian

III. Recommendations 8

Appendix A. A Commercial Diving Course Curriculum 12

Appendix B. A Community College Commercial Diving Course Curriculum 19

Appendix C. Representative University Curriculum 27

Abstracts 31

Selection and Training of Professional Divers

The panel began with a discussion of psychological factors as delineated in the original plan for the work group: personality changes in divers, stress and social interaction, and selection and training. It was generally agreed that the areas of personality changes and social interaction are not the critical problems that had been anticipated in early considerations of diving operations. Although laboratory research on isolation and confinement suggested that individuals in close quarters under stress of confinement would exhibit personality difficulties especially in social interaction, this concern has not materialized in the large number of habitat and hyperbaric chamber experiences over the last 10 years.

There are many reasons for this. One conjecture is that the laboratory experiences with social isolation and confinement were such that the subjects were, in effect, able to escape the situation (even though some negative consequences might result), whereas in hyperbaric conditions with subjects under pressure, the individual cannot leave the isolation situation and thus, presumably, accommodates to it. Stress and social interaction as they relate to diving, therefore, are not considered to be important enough to warrant further research at this time. Social interaction in terms of selection did strike the panel as being of importance and will be considered in more detail in a later section of this report. Personality changes in divers also are believed to be a nonsignificant problem inasmuch as there is no evidence of marked changes in personality in divers over a period of years. If anything, it is believed that divers with more experience and more maturity are actually more confident and less anxious. There is, of course, much self-selection in the diving industry, as evidenced by the fact that those divers who are consistently inadequate in their performance or who lack the will or drive to continue diving leave the diving industry.

Accordingly, the panel decided to concentrate its attention on the important problem of the selection and training of divers.

I. Basic Concepts in Selection and Training

A. Diver Selection

As with all volunteer situations, divers elect to be trained. Commercial divers learn diving as a means to an end: earning a living and applying their skills in an industrial setting. Divers in academic institutions and government learn diving to conduct either research or work programs. U.S. Navy divers are trained for many work tasks as well as tactical missions.

The Navy's attempts to find sensitive measures for selecting future divers have not been overly successful. Measures of intelligence (Berghage 1972) and standard personality measures have proved to be only marginally successful at best (Radloff and Helmreich 1968).

Two areas of measurement that hold possible promise for future work are physical fitness and demographic history. A pilot study presently underway by Knight, Brady, and Berghage has been evaluating a select group of gross physical fitness measures and their ability to predict success in Navy diver training. The various tests being used in the Knight et al. study to test physical fitness were selected using factor analytic techniques, and preliminary results indicate that several of the measures (strength, stamina, and flexibility) correlate with both underwater performance and overall success in the Navy's diver training program. Similar results relating to underwater performance appear in Egstrom and Weltman (1974) and Bachrach (1975). Demographic history, the other measure that holds promise, was evaluated several years ago by Radloff (1971). Using a diving history questionnaire developed at the Naval Medical Research Institute, Bethesda, Md., during the SEALAB project, Radloff was able precisely and effectively to predict success in the Navy's Diver Second Class training program. Helmreich, Wilhelm, and Bakeman (1971) concluded that a Life History Questionnaire used on TEKTITE II was a most effective predictive test, applicable both to research into the antecedents of behavior and to the selection of candidates for specialized roles. Biersner and Ryman (1974) were also successful in predicting performance using a demographic questionnaire, along with health and attitude scales, on trainees for Diver Second Class.

Current selection criteria for divers are based on the evaluation of past performance, cognitive and motor skills, motivation, and physical and psychological health. Past performance criteria, especially educational accomplishments, have often been found to be good predictors of success in diving. Physical stamina and emotional maturity have similarly been found to be essential for the successful performance of work tasks, especially those performed under hazardous or difficult working conditions. Fortunately, measures of physical stamina can be objective, e.g., a man can/cannot swim 1000 ft; he does/does not have evidence of ischemic heart change on a stress EKG. Emotional maturity and motivation, although more difficult to measure, have been evaluated by various pencil-and-paper studies although, as noted above, without distinguished success. It is important to point out that the nature of diving tasks over the past few years has increased both in complexity and sophistication, requiring a class of divers having more skills and talents.

The following criteria are used by modern commercial diving training schools for the selection of diving trainees:

1. Age--Most schools prefer to select divers between the ages of 22 to 29, with a mean age of 24 years. It is generally believed that divers beyond this range have a limited life span of work as a diver, while those applicants under the age of 22, generally speaking, are not experienced enough in work skills to perform satisfactorily with only a short course of instruction.

2. Certified sport diver--It has generally been found that those individuals already certified as sport divers make better candidates for commercial diving training.

3. Marital status--Schools prefer single men because of travel and offshore requirements; at the present time about 75% of those candidates selected for training are single. This percentage is, however, decreasing.

4. Education--At the present time commercial diving training schools require that applicants selected have a high school degree or equivalent. Approximately 50% of the commercial diving students have some college and 18% have college degrees.

5. Veteran status--It has been found that veterans make better diving candidates, presumably because they are better disciplined and have had experience in working groups.

6. Written tests--Tests involving mechanical, reasoning, and mathematical abilities are normally used in addition to the other selection criteria.

7. Medical examinations--All candidates must have a thorough medical examination. In addition to looking for physical factors such as cardiac difficulties and neurological problems, experience has shown that a history of back injury is strongly contraindicative to selection. The National Planning Panel on the High Pressure Nervous Syndrome (HPNS) has suggested that an important medical criterion for deep dives is individual susceptibility to the HPNS and that personnel selection for this factor is important and seems realizable in principle provided appropriate selection criteria can be determined.

All of the above items are put into a selection profile and are weighted in the selection of diving candidates. The following is a list of additional criteria that are perhaps less tangible, but they do play a role in selection. Diving candidates need: (1) a realistic attitude toward diving as a profession; (2) a good general academic aptitude, including mathematics and chemistry; (3) some general ocean background, such as surfing, lifeguarding, swimming, etc., which gives a distinct advantage to the general "waterman" concept; and (4) additional experience with mechanical hobbies, such as working on automobiles, building airplanes, and the like. In recent years there has been an increasing emphasis on mechanical aptitude and skills as a result of feedback from the field.

Performance criteria are accepted by industry in preference to classroom knowledge. They are used to predict success in the completion of diving courses. An instructor's intuitive reaction coupled with performance criteria is, at present, the best combination to assess the probability of a diver's ultimate success.

B. Diver Training

Each candidate for underwater work must be given a minimum core curriculum and a practical period of experience before he can be considered a safe and competent diver. Additional training in specialized areas is then needed for application of these diving skills to other new or preexisting skills. Professional divers must develop these skills and associated appropriate attitudes to complete their tasks successfully and safely. Formal training, either from university-based programs or commercial diving schools, provides the most appropriate means for the transfer of the requisite skills and attitudes, supplemented by in-house training.

Formal training programs allow for a more uniform and consistent delivery of knowledge and skills. They provide quality control in the selection and education of the divers. They provide a medium through which industry may give input concerning its needs so that the man trained may be employed at the completion of his training. University-based programs provide the specific research techniques needed for a given scientific program after the basic knowledge and skills have been taught to the diver and demonstrated by him.

To plan training programs effectively it is necessary to have criteria for the actual behaviors in which the diver will engage; diver task analysis and job descriptions are crucial.

1. Diver task analysis

A general description of the tasks performed by professional divers has been stated by Liffick (1971). For purposes of this report, however, the tasks have been condensed into six categories, with some modification:

1. Construction
2. Maintenance and repair
3. Inspection
4. Science and research support
5. Training
6. Search, recovery, salvage, and rescue

These tasks are carried out in one or more of four major system categories:

1. Industrial--primarily offshore oil, construction, and maintenance.
2. Government--both military and non-military
3. Civilian sector--primarily police, fire, and rescue organizations.
4. Universities--primarily to conduct research and scientific support as well as recreational enterprises. (The latter will not be included in this report.)

The Association of Diving Contractor's Manual of Safe Practices in Commercial Diving Operations (1974) divides personnel engaged in diving activities into two groups: diving personnel and tending personnel. Their designations indicate personal degrees of qualification and are not to be construed as defining the title, responsibility, or duties that may exist on an individual job or for a given employer.

a. Diving Personnel (listed from most to least qualified)

1) Systems Diver--Qualified to personally conduct underwater work using mixed gas and air techniques (includes saturation divers).

2) Divers--Qualified to personally conduct underwater work using air techniques.

3) Diver/Tender--Qualified to conduct underwater work under supervision of fully qualified diving personnel and to tend divers.

b. Tending Personnel (listed from most to least qualified)

1) Professional Tender--Qualified to independently tend and decompress divers and to operate surface support equipment (equivalent to Life Support Technician).

2) Tender--Qualified to tend divers and to operate surface support equipment under the supervision of fully qualified diving and/or professional tending personnel.

c. The panel's recommendations for classification

This panel recommends a somewhat different terminology from the ADC one:

1) Supervisor--Qualified to be in charge of diving operations; has final authority with respect to safety operations.

2) Life Support Specialist--Qualified to personally conduct underwater work in a specific area, e.g., rack operation, gas analysis, saturation system, medical treatment, and chamber operation.

3) Diver--Qualified to personally conduct underwater work using mixed gas and air techniques (includes saturation divers).

4) Tender--Qualified to tend divers and to operate surface support equipment under supervision.

The following operational model for personnel may be coupled with a training model to provide an overview of diving operations.

C. Operational Model

Diving Proficiency + Technical Proficiency + Field Experience

D. Training Model

Skills Already Acquired + Basic Knowledge
(a factor in selection
for training)
+
Advanced Skill Training + Field Experience

The criteria involved in the training model are:

1. Skills already acquired--Those skills and attitudes which exist prior to diving training which may or may not be immediately applicable to diving-oriented tasks.

2. Basic knowledge--The minimum amount of knowledge needed to allow a diver to dive safely and successfully. (This knowledge is outlined in the description of formal training programs.)

3. Advanced skill training--Those skills which allow a diver to be more proficient in completing his tasks, to complete tasks of greater complexity, or to learn new tasks. This category also applies to life support technician and underwater emergency medical technician skills. The latter category is currently under study.

Diver task analysis and functional description of field performance will contribute to more meaningful criteria for selection and training.

II. Major Sectors Involving Professional Divers

We will now turn specifically to a consideration of the major sectors involving professional divers.

A. Industrial sector

A commercial diver is a skilled technician vital to some important undersea activity, such as offshore oil drilling operations, underwater construction, installation of complex equipment, or salvage operations. A prime source of employment is in the offshore oil industry. In addition to diver training, consideration of the entire task indicates training for the entire support crew, including tenders, rack operators, and life support specialists.

A typical commercial diving training program would include a Basic Air/Mixed Gas Diving course. This course would provide basic training in preparation for commercial diving. It would include a study of major diving equipment and its functions in underwater work, and would be designed to introduce the student to diving techniques and their practical application for offshore oil field diving, construction, maintenance and repair, inspection, and search, salvage and recovery.

An advanced program not currently available in all diving schools is a Bell/Saturation Diving advanced course. The course is a practical application in bell/saturation diving techniques. Emphasis is placed on developing technical and supervisory personnel qualified to operate a bell/saturation system. This is an advanced course designed to develop the highly skilled bell/saturation diver technician needed in today's diving industry. The course trains the student in bell/saturation diving as a diver, diver tender, gas rack operator, environmental control specialist, diving supervisor, etc.

Another advanced course of growing importance is Medic Training. This underwater emergency program meets the diving industry's need for qualified emergency medical personnel specially suited to the requirements of offshore operations. It provides the skills and knowledge to ensure immediate, responsible medical assistance at the site of an accident. Emphasis is on proper clinical diagnosis and treatment to provide optimum care between the time of evacuation to a medical facility and/or the arrival of a physician. The program stresses theoretical and practical understanding of basic emergency medicine.

A commercial diving course curriculum for three courses appears as Appendix A: Basic Air/Mixed Gas Diving; Bell/Saturation Diving; and Underwater Emergency Medical Technician. The curriculum is based on courses offered at the Commercial Diving Center. A list of commercial diving schools is included.

Another type of commercial diver training program is offered in several community colleges. The principal objectives of this type of program are also to train qualified personnel for the diving service industry. As employees in the diving industry, the graduates of these programs work primarily in conjunction with the worldwide exploration for and production of offshore petroleum. These programs are intended to be terminal at the end of the two years of instruction without further college experience; that is, the graduates are prepared for job entry at the time of graduation.

The curricula contain essentially three types of courses. The first is designed to give the student the required skills and knowledge in contemporary diving equipment and procedures as well as the related mechanical and technical areas. The second type of course is designed to give the students a knowledge of the ocean and its environment. The third course is designed to increase communicative abilities.

Programs such as the one at Santa Barbara City College are under the guidance of an Advisory Committee consisting primarily of supervisory personnel from the diving industry and other specialists in related fields. The course curriculum for this program appears as Appendix B. A listing of other community colleges offering similar programs is included.

It should be noted that the course curriculum of the Commercial Diving Center basic course contains 420 hours and is taught in 15 weeks. The Santa Barbara City College course contains 550 diving class hours (with additional subjects as separate hours) taught over a 2-year academic period.

B. University sector

The University diving sector involves a cross-section of the scientific and research community: biologists, geologists, marine botanists, chemists, oceanographers, physicists, physiologists, and engineers; faculty, staff and students.

Diving is rarely a full-time job, but rather serves as the means by which the trained scientist or researcher may safely conduct research underwater.

Appendix C is a representative university curriculum in scientific/research diver training from Scripps Institution of Oceanography. The items included under each rubric are only a part of each section as taught and are used as illustrations of content. Other representative university programs are also listed in Appendix C.

C. Governmental sector

Civilian divers in the employment of the federal government rarely dive on a full-time basis. Rather, they have other specialized skills such as engineering, scientific training, or marine technology. When a major diving project is undertaken, professional divers are obtained from industry. Divers are located in many nonmilitary federal agencies, including the Coast Guard, Corps of Engineers, NOAA, Department of Interior, and Smithsonian Institution. Diving tasks include repair and maintenance of ships, employment and maintenance of oceanographic instrumentation and fishing gear, marine scientific investigation, and biomedical experimentation. Increasing numbers of marine scientists are using diving to augment surface-based oceanographic research. Training for government divers is usually carried out by nationally recognized scuba training organizations, rather than at commercial diving schools.*

D. Civilian sector

Diving in the civilian sector is generally performed by scuba divers employed by organizations such as police and fire-rescue, which require search and rescue and recovery and salvage.

These divers may be former military divers who are presently employed in a Police or Fire Department and who have collateral diving responsibilities. Other sources include sports and commercial divers who volunteer their services. Small organizations must rely on "volunteers" and have little or no input into the volunteer's training. The specialized training needed for deep recovery operations, such as diving in strong current or heavily polluted waters, is not always a part of a volunteer's training.

III. Recommendations

Research needs in order of proposed priority:

1. Manpower needs should be delineated to assess the possible requirements for the establishment of new specialized schools of training or the enlargement of existing schools. One datum needed would be the projection of the possible opening of new oil fields or construction requiring additional personnel.

---

*These organizations include: NAUI, PADI, YMCA, NASDS, and courses are normally available in the trainee's community.

2. A central record depository should be established in which copies of the nature and level of all training courses attended, yearly experience etc., is kept on every diver attending a course for professional diving. Each diver should keep and maintain a copy of this log which must be updated yearly. Should the diver leave the profession he should be required to return his log to the central depository; each diver should be required to state his reasons for leaving the profession before being released from his job. Should he wish to dive professionally again, he would be required to re-apply for his training and experience log book. Reasons for leaving the diving profession ought to provide a valuable research source.

3. Research into attrition rates in commercial diving; in particular, a study of the characteristics of divers who remain in commercial diving, with the goal of developing improved selection criteria for training programs.

4. Research to develop diving statistics, possibly derived from the U.S. Navy format (Berghage, Rohrbaugh, Bachrach, and Armstrong--in preparation), with the matrix provided in Table 1.

Table 1

Data obtained and analyzed for each recorded Navy dive

	Variables	
Procedural	Environmental	Personnel
Type of equipment used	Dive depth	Height
Type of diving dress used	Bottom time	Weight
Equipment performance	Breathing media	Weight-height ratio
Purpose of dive	Air temperature	Body build
Tools used	Wave height	Age
Decompression schedule used	Surface water temperature	Marital status
Decompression location	Bottom water temperature	Type of work
Class diver	Current	Did an accident occur?
	Bottom type	
	Visibility	

From Berghage, Rohrbaugh, Bachrach, and Armstrong, in preparation.

5. A mechanism for formal feedback from industry to training programs regarding needed changes and additions. This should include information that would keep programs current with industry needs and diving practices, projected and current diving procedures, and advances in equipment design and usage. Research into needs for subsidizing such programs is important.

6. A clear set of guidelines for personnel qualification by specific job description.

7. An evaluation of chemical agents (i.e., alcohol and other drugs such as antihistamines and marijuana) and pressure interactions with an assessment of possible deleterious effects on training and performance.

8. All divers should be trained to handle basic life saving action for medical emergencies. Guidelines should be developed for this training activity in all commercial diving schools. The recommendations concerning the training of Diver Life Support Specialists who would have extensive training in handling medical emergencies are contained in Report 5T.

REFERENCES

(1) Association of Diving Contractors, 1974. Manual on Safe Practices in Commercial Diving Operations.

(2) Bachrach, A. J. 1975. Underwater performance. In: The Physiology and Medicine of Diving and Compressed Air Work. 2nd ed. London: Bailliere Tindall, p. 264-268.

(3) Berghage, T. E. 1972. The use of standard Navy classification test scores for the selection of diver first class candidates. U.S. Navy Experimental Diving Unit, Washington, D.C., 15 August 1972. Report No. AD763346.

(4) Berghage, T. E., P. A. Rohrbaugh. A. J. Bachrach, and F. W. Armstrong. (in preparation) Navy diving: Who's doing it, and under what conditions. U.S. Naval Medical Research Institute, Bethesda, Maryland.

(5) Biersner, R. J., and D. H. Ryman. 1974. Prediction of scuba training performance. J. Appl. Psychol. 59(4):519-521.

(6) Egstrom, G. H., and G. Weltman. 1974. Underwater work performance and work tolerance. Final Report, UCLA-ENG-7427. University of California School of Engineering and Applied Science, Los Angeles.

(7) Helmreich, R., J. Wilhelm, and R. Bakeman. 1971. Prediction of in-habitat behavior. In: TEKTITE 2: Scientists-in-the-sea. p. VIII-30-59. U.S. Department of the Interior, Washington, D.C.

(8) Knight, D., T. H. Farrier, J. I. Brady, Jr., and T. E. Berghage. (in preparation) Predicting success in Navy diver training. U.S. Naval Medical Research Institute, Bethesda, Maryland.

(9) Liffick, G. L. 1971. Hydraulic tools and equipment for underwater salvage. In: Marine Technology Society 7th Annual Conference. (Preprints).

(10) Radloff, R. 1971. Life history and success in diving school. U.S. Naval Medical Research Institute, Bethesda, Maryland.

(11) Radloff, R., and R. Helmreich. 1968. Groups Under Stress: Psychological Research in SEALAB II. New York: Appleton-Century-Croft.

APPENDIX A

A Commercial Diving Course Curriculum

For

Basic Air/Mixed Gas Diving

Bell/Saturation Diving

Underwater Emergency Medical Technician

based on

Commercial Diving Center Courses

also:

Listing of Commercial Diving Schools (private)

Underwater Emergency Medical Technician

Course content

Course content includes:

- Terminology of Anatomy and Medicine
- Patient Evaluation and Vital Signs
- Chest Anatomy--Physiology and Disease; Airway Resuscitation
- Heart Anatomy--Physiology and Disease; Cardio-pulmonary Resuscitation
- Extremities--Fractures, Splinting, and Bandaging
- Abdomen and Pelvis Anatomy and Injury
- Neurological Examination
- Medical Emergencies--Coma, Overdose, Poisoning
- Splinting and Backboards
- Shock, Burns, and Drowning
- Cold/Hot Environmental Disorders
- Pharmacology--Fluid Management
- Psychiatric Disorders
- Triage and Evacuation
- Legal Considerations
- Chest Tubes and I.V.'s
- Diving Treatment Procedures
- Hyperbaric Chamber Operation
- Coroner Sessions
- Clinical Sessions

Air/Mixed Gas Diving

Section I - Physics & Physiology Related to Diving

- Physics
- Anatomy & Physiology
- Primary & Secondary Effects of Pressure on the Human Body
- Medicine
  - Type
  - Symptoms
  - Prevention
  - Cause
  - Treatment
- Emergency First Aid for Divers

Section II - Diving Tables

- Decompression Tables
  - Standard air tables
  - Repetitive dive tables
  - Surface decompression tables
- Treatment Tables
  - Signs and symptoms
  - Recurrence of symptoms during and after treatment

Section III - Diving Equipment

- Function and Nomenclature of Diving Equipment
  - Lightweight
  - Heavy gear
  - Scuba
- Diving Techniques and Procedures
- Emergency Procedures

Section IV - Underwater Burning and Welding

- Introduction to U/W Cutting and Welding
- Oxy-Arc Cutting Techniques
- Practical Application of Burning
- Practical Application of Welding
- Surface Burning and Welding (Basic)

Section V - Hyperbaric Chamber

- Nomenclature
- Operation
- Pressure Test
  - Standard
  - O_2 Tolerance
- Decompression/Recompression Procedures

Section VI - Introduction to the Application of Diving Techniques

- Underwater Equipment
  - Heavy gear
  - Lightweight

Section VII - Repair and Maintenance of Diving Equipment

- Lightweight Equipment
  - General maintenance and repair
- Heavy Gear
  - General maintenance and repair
- Diving Dress/Wet Suits
- Lifeline and Air Hose
- Communication

Section VIII - Salvage and Rigging

- Rigging Fundamentals
- Application of Rigging
- Salvage Theory
- Types of Salvage
- Gas Hazards and Dewatering
- Preparations for Salvage Operation

Section IX - Diesel Engine and Air Compressor Theory

- Orientation
  - Scope and purpose
  - Safety procedures
- Basic Theory of Diesel Engine
- Air Systems
- Fuel Injection Systems
- Cooling Systems
- Lubrication Systems
- Basic Theory Air Compressor
- Maintenance
- Starting Procedures

Section X - Underwater Explosives

- Introduction to Underwater Demolition and Salvage
- Application of Explosives
- Characteristics of Underwater Explosives
- Firing Systems and Equipment
- Effects of Underwater Blasts on the Human Body

Section XI - Application of Diving Techniques

- Underwater Project (Open Water)
  - Heavy gear

Section XII - Oilfield Diving

- Introduction to Oilfield Diving
  - Exploration rig diving
  - Subsea drilling
  - Production diving

Section XIII - Minimal Oxygen Treatment Tables

- Introduction
- Application

Section XIV - Application of Diving Techniques

- Underwater Project
  - Lightweight equipment

Section XV - Mixed Gas Diving

- History of Diving
- Function and Nomenclature of Mixed Gas Diving Equipment
  - Deep sea
  - Lightweight
- Formulas Used in Mixed Gas Diving
  - Maximum O_2
  - Effective O_2 partial pressure
  - Cutoff depth

        - Helium partial pressure
    - Manifold Operation
    - Practical Application of Mixed Gas Diving

Bell/Saturation Diving

Section I - Course Introduction and Indoctrination

- General Information
- Trainee's Duties and Responsibilities
- Course Requirements for Graduation
- Pre-Course Trainee Evaluation

Section II - Study of Offshore Diving

- Operations
    - Drilling vessels
    - Offshore platforms
    - Lay barges - pipeline installation
    - Jet barges - pipeline lowering
    - Live boating
- Jobs
    - Stubs
    - Methods of search and location
    - Subsea completions
    - Miscellaneous salvage
    - Inspection of drilling vessels and offshore platforms
    - Loading out equipment

Section III - Advanced Underwater Cutting

- New Techniques and Equipment
- Equipment Set Up
- Cutting Projects

Section IV - Applied Diving Physiology in Saturation Diving

Section V - Diving Medicine in Saturation Diving

Section VI - Support Equipment

- Air Compressors
    - Types, sizes, and uses
    - Compressor output and diver demands
    - Operation
    - Upkeep and servicing
    - Maintenance and minor repair
- Jet Pumps
- Volume Tanks
    - Design and construction
    - Coding
    - Care and upkeep

- High Pressure Systems
    - Safety
    - Testing
    - Manifolds
    - Maintenance
- Diver Phones
    - Types - Air/Mixed Gas
- Head Gear
    - Open systems
    - Closed systems
- Chambers
    - Types and uses
    - Maintenance
    - Construction coding
    - Proper set up and operation

Section VII - Advanced Air Diving
- Diving Tables (Review)
    - Standard
    - Sur-D
    - Repetitive
    - Treatment tables
- Other Decompression Tables
    - Haldane's Theory
    - British/Brian Hill's work
    - Miscellaneous tables

Section VIII - Diving Safety Procedures
- System setup
- Daily Checks
- Pre-Dive Checks
- Live Boat Diving

Section IX - Advanced Helium-Oxygen Diving
- Standard Navy Tables
- Commercial Tables
- Equipment
- Safety Procedures
- Personnel Duties and Responsibilities
- Mixing Gas

Section X - History of Bell Diving
- Davis Bell
- Hockett Bell
- Purisima
- Galeazzi Bell
- Progression to Today's Bells

Section XI - Bell Design
- Types of Bells
- Lock on System
- Structural Advantages and Disadvantages
- Federal and State Regulations

Section XII - "Standard" Bell
- Systems Control
- Operation
- Diver's Equipment

Section XIII - Deck Decompression Chamber
- DDC Design
- Life Support/Environmental Control Systems

Section XIV - Handling (Launching) System
- Construction
  - Advantages and disadvantages

Section XV - Application of Bell System (Theory)
- Personnel
- Setup
- Deep Diving

Section XVI - Deep Water Tools
- Types
  - Advantages and disadvantages
  - Application

Section XVII - Dry Welding Habitat/Alignment Frame Systems

Section XVIII - Bell Diving Theory
- Partial Saturation
- Total Saturation

Section XIX - Application of Bell Diving
- Atmospheric Bell Diving
- Ambient Bell Diving
- Atmospheric and Ambient Bell Diving
- Bell Operation/Projects
- Saturation Mode/Sat Dives
- Projects

Section XX - Practical Application of Course
- Deep Air
- Mixed Gas

Commercial Diving Schools (private)

- Coastal Diving Academy, New York (not affiliated with school in Oakland)
- Coastal Diving School, Oakland, California
- Commercial Diving Center, Wilmington, California
- Diving Institute of Technology, Seattle, Washington
- Diver Training Academy, Fort Pierce, Florida
- Ocean Corporation, Houston, Texas

APPENDIX B

A Commercial Diving Course Curriculum
Offered by Community Colleges

from

Santa Barbara City College

also:

Listing of Commercial Diving Schools: Community Colleges

1973-74 Marine Technology Curriculum

Course No.	First Semester Program	Lecture Hours	Lab Hours	Units
M.T. 1	Seamanship and Small Boat Handling	2	4	3
M.T. 2	Basic Diving	2	4	3
I.T. 2	Drawing and Blueprint Reading	1	6	3
Weld 1	Basic Welding	1	3	2
Eng 18 A	Technical Report Writing	1	2	1 1/2
Humanities		3	0	3
		10	19	15 1/2

	Second Semester Program			
M.T. 3	Advanced Diving	2	4	3
M.T. 4	Fundamentals of Marine Engines and Compressors	2	3	3
Weld 3	Marine Welding	1	3	2
Eng 18 B	Technical Report Writing	1	2	1 1/2
E.S. 11	Physical Oceanography	3	3	4
Biol 5	Marine Biology	2	3	3
		11	18	16 1/2

Students deficient in Math will be required to take Math 41 & 43.

Summer Session: Marine Technology 11 - Summer Cooperative

Marine related work experience (1-4 units), one unit of credit per 75 hours of work.

	Third Semester Program			
M.T. 5	Underwater Construction	2	4	3
Biol 11	Biological Oceanography	2	3	3
Phys 11	Technical Physics	3	3	4
Elec 10	Fundamentals of Electronics	2	3	3
M.S. 11	Machine Shop Operations	2	6	4
		11	19	17

	Fourth Semester Program			
M.T. 6	Underwater Operations	2	4	3
M.T. 7	Diving Systems	2	4	3
Phys 12	Technical Physics	3	3	4
Speech 5	Business Speech	3	0	3
Amer Inst*		3	0	3
		13	10	16

*Note: American Institutions is required for the Associate in Science degree.

Students with advanced standing and above average grades may elect to take credit for independent study in:

M.T. 21-22 Research Module (1-3 units)

Recommended electives: Marine Technology 11, 21, 22, 30 50 and 67.

Santa Barbara City College Course of Study Outline

Marine Technology 1 - Seamanship and Small Boat Handling (3)

Nature of the Course

Description: An introductory course designed to acquaint the student with the technical skills required in Marine Technology. A survey of job opportunities and career potentials in the various areas of Marine Technology. This course will familiarize the student with basic rigging techniques and procedures, as well as navigation, piloting and small boat handling.

Grade level: Freshman

Hours per week: Six (6)

Organization: Two (2) hours lecture - demonstration and four (4) hours laboratory per week.

Prerequisites: None

Marine Technology 2 - Basic Diving (3)

Nature of the Course

Description: Introduction to diving. Designed to parallel other recognized "100 hour" diving courses. Satisfactory completion results in both S.B.C.C. and Los Angeles County certification. S.B.C.C. certification may be extended beyond one year period, providing the individual maintains his student status and fulfills the requirements for maintenance of certification. A minimum of twelve (12) ocean "working" dives, using both SCUBA and surface-supplied diving equipment.

Grade level: Freshman

Hours per week: Six (6)

Organization: Two (2) hours lecture and four (4) hours lab

Prerequisites:

Appropriate medical examination attesting to the student's physical fitness for diving.

Execution of required release and waiver

Satisfactory performance of swimming and skindiving tests

Aims and Objectives

Marine Technology 3 - Advanced Diving

Nature of the Course

Description: An introduction to the use and care of the following equipment: Lightweight and heavy gear (hard hat) diving equipment, mixed gas, mixed gas manifold and decompression chambers. The physics and physiology of mixed gas and the treatment of diving accidents and diseases are included in this course.

Grade level: Freshman

Hours per week: Six (6)

Organization: Two (2) hours lecture and four (4) hours laboratory per week.

Prerequisites: Marine Technology 1 and 2 or by permission of instructor.

Marine Technology 4 - Fundamentals of Marine Engines and Compressors (3)

Nature of the Course

Description: A course designed to familiarize the student with the principles of the operation and maintenance of marine engines and diving compressors. Emphasis will be placed on an understanding of function and theory, proper operation, troubleshooting and replacement of components.

Grade level: Freshman

Hours per week: Five (5)

Organization: Two (2) hours lecture - demonstration and three (3) hours lab - practical shop experience - per week.

Prerequisites: Marine Technology I or permission of instructor.

Aims and Objectives

General

To familiarize the student with various types of marine engines and diving compressors.

To impress the student with the importance of the proper use and care of this type of equipment.

Skills and abilities

Marine Technology 5 - Underwater Construction (3)

Nature of the Course

Description: A practical application in underwater construction techniques. Stress will be placed on the student developing skill and proficiency in using tools and performing underwater work commonly encountered by a commercial diver. Diving equipment used, and procedures learned, in previous diving classes will be incorporated into the course.

Grade level: Sophomore

Hours per week: Six (6)

Organization: Two (2) hours lecture demonstration and four (4) hours practical lab per week.

Prerequisites: Marine Technology 1 through 3 and Welding 1 and 3 or permission of instructor.

Marine Technology 6 - Underwater Operations (3)

Nature of the Course

Description: A course designed to familiarize the student with, and offer practical training in, current offshore and marine construction operations, equipment and procedures. Emphasis is placed on the diver's role and the application of skills and knowledge acquired in the preceding courses.

Grade level: Sophomore

Hours per week: Six (6)

Organization: Two (2) hours lecture demonstration and four (4) hours practical lab per week, plus a four (4) hour field trip.

Prerequisites: Marine Technology 1 through 5, plus Welding 1 and 3 or by permission of instructor.

Marine Technology 7 - Diving Systems (3)

Nature of the Course

Description: A course designed to familiarize the student with current commercial diving systems and their components. Emphasis to be placed on incorporating diving technology principles learned in Marine Technology 1 through 5 into bell, saturation, dry welding and alignment systems.

Grade level: Sophomore

Hours per week: Six (6)

Organization: Two (2) hours lecture-discussion and four (4) hours lab

Prerequisites: Marine Technology 1 through 5, plus Welding 1 and 3, and concurrent registration in, or previous completion of, Marine Technology 6.

Marine Technology 21-22 - Research Module (1-3) F.S.

Nature of the Course

Description: This is a variable unit course (1-3 units per semester) which may be repeated once for a maximum of six (6) units. The course would be conducted on an independent study basis under the direction of the College Diving Officer acting as coordinator for the program. Admission to the course would be determined by an interdisciplinary faculty committee. This committee would consist of representatives from Life Science, Physical Science, and Vocational-Technical Divisions. The committee would admit only those students who are properly qualified for the course. Admission to the course would entail the following: a. the student submit a plan of his research module or independent research project; b. the student would include in his proposal an outline and/or a diagram for the project selected for further study. If the student is admitted, he would be required to maintain a log of time spent on the project and would meet frequently with the College Diving Officer and appropriate faculty advisor to discuss the student's progress and to help resolve any problems which might develop.

The purpose of the course is to enable Marine Technology students to apply their previous academic or vocational disciplines and make use of the facilities and equipment of the College and community to further his study in the design, construction and utilization of the research module as a staging area for the expansion of knowledge in marine biology, oceanology, geology physics, electronics and marine construction. This course will enable the student to make a positive contribution to the improvement of the Marine Technology Program at the College and will provide additional opportunities for educational growth and experience not available in the traditional college curricula.

Grade level: Freshman or Sophomore

Hours per week: 4 to 16

Organization: To be determined by agreement with faculty advisor

Prerequisites: Advanced standing in Marine Technology and by invitation from faculty advisor.

Marine Technology 11 - Summer Cooperative Work-Study (1-4 units)

Nature of the Course

Description: A specialized work/study program designed to give the student supervised practical experience in the application of skills and knowledge learned in related classes in the Marine Technology program. Employment may be obtained subsequent to enrollment. One unit of credit allowed for each seventy-five (75) hours of satisfactory paid employment completed during the summer, up to a maximum allowable of three hundred (300) hours.

Grade level: Sophomore

Hours per week: Eight (8) to forty (40)

Organization: Practical duties as assigned by employer.

Prerequisite: Enrollment in Marine Technology program. Student either employed or available for employment in a related field of marine science and industry.

Marine Technology 30 - Supervised Ocean Diving (1/2)

Nature of the Course

Description: Practical ocean diving exercises, using lightweight and heavy gear (hard hat) diving equipment, mixed gas, mixed gas manifold and decompression chambers.

Grade level: Freshman

Hours per semester: Twenty-four (24)

Organization: Three (3) offshore labs of eight (8) hours each, schedules during the semester.

Prerequisites: Marine Technology 1 and 2 or by permission of instructor and concurrent registration in Marine Technology 3 - Advanced Diving.

Marine Technology 50 - Supervised Ocean Diving (1/2)

Nature of the Course

Description: Practical ocean diving exercises in using the tools and performing underwater work commonly encountered by the commercial diver. Diving equipment used and procedures learned in previous diving classes will be incorporated into the labs.

Grade level: Sophomore

Hours per semester: Sixteen (16)

Organization: Two (2) offshore labs of eight (8) hours each scheduled during the semester.

Prerequisites: Marine Technology 1, 2, 3 and Welding 1 and 3, and permission of instructor, and concurrent registration in Marine Technology 5 - Underwater Construction.

Marine Technology 67 - Supervised Ocean Diving and Lecture/Demonstration (2)

Nature of the Course

Description: Practical ocean diving exercises on offshore installations and performing tasks commonly encountered by the commercial diver, plus lecture-demonstration in the use of underwater explosives.

Grade level: Sophomore

Hours per semester: Forty-eight (48)

Organization: Four (4) offshore lab exercises of eight (8) hours each and two (2) lecture-demonstration sessions of eight (8) hours each.

Prerequisites: Marine Technology 1 through 5, plus Welding 1 and 3 or by permission of instructor, plus concurrent registration in Marine Technology 6 - Underwater Operations and Marine Technology 7 - Diving Systems.

Commercial Diving Schools: Community Colleges

Florida Institute of Technology
Jensen Beach, Florida

Highline Community College
Midway, Washington

Santa Barbara City College
Santa Barbara, California

APPENDIX C

Representative University Curriculum

from

Scripps Institution of Oceanography

also:

Listing of Other Representative University Programs

Physics of Diving, including:

- Gas laws
- Underwater sound
- Temperature-related problems

Anatomy, including:

- General Anatomy, with an emphasis on:
  - Circulatory
  - Respiratory

Physiology, including:

- Respiratory
- Circulatory
- Effects of different breathing gas mixtures

Diving Diseases, including:

- Air embolism
- Bends
- Inert gas narcosis

Equipment Review and Characteristics, dealing with such items as:

- Masks
- Fins
- Diving suits
- Regulators
- Tanks
- Other diving equipment

Oceanography, including

- Characteristics of waves
- Properties of water
- Currents

Decompression

Review of the physiology of decompression among other topics such as the use of repetitive tables.

Seamanship/Small Boat Handling, including such techniques as:

- Knot tying and splicing
- Dead reckoning

SCUBA Regulators and General Diving Locker Procedures dealing with such topics as:

- Breakdown and overhaul of regulators

Scuba tank inspection
Filling procedures

Underwater Photography

Types and use of various cameras including movie and still.

Scientific Collecting Techniques

Transportation and preservation of specimens of various types.

Mammals

Live collection of mammals by techniques such as tranquilizers and net traps.

Dead specimens, by techniques such as shooting and harpooning

Collection of other specimens such as fish and invertebrates as well as geological and sediment specimens is detailed.

Marine Hazards

Environmental hazards and potentially dangerous marine animals
- Pelagic, including:
  - sharks
  - whales
- Rocky areas, including:
  - eels
  - crabs
  - venomous fish
- Sand or sediment, including:
  - sting rays
  - electric rays
  - cone snails
- Fresh water, including:
  - rivers
  - lakes
  - ice
  - monofilament line
  - underwater hazards such as trees

Search and Recovery (near shore line--not covered under seamanship)

Relocation Techniques, use of Fathometers, sextants, and other equipment.

History and Current State-of-the-Art of Diving, dealing with the development of diving techniques and equipment.

Physical Exam, including stress EKG, vision, blood, urine, audiometry and x-ray

Pretraining Tests
Pool

Swimming tests:
75 feet underwater
1000 feet in 10 minutes
150 feet underwater with breaths
Recover victim of equal size and tow 75 feet
Ocean (open water)
1000 feet open water swim
surf passage

Other techniques such as emergency ascent without air are taught, as well as water entries and bail out.

SCUBA Dives (12)

Dives are structured from easy to difficult and include experience in:
Use of lifting devices
Vertical buddy breathing
Ocean lifesaving under varying conditions of rocks, sand, boat and pier.

Basic Cardio-pulmonary Resuscitation according to American Red Cross or American Heart Association Basic First Aid pertaining to potential diving problems.

Final written exam based upon knowledge of reading assignments. Certification by board. Many colleges, universities, and agencies employ the same training and certification policies and, therefore, enjoy a workable reciprocity based on this common training. In addition, a nationally recognized scuba certification is usually available to university-certified divers.

Other Representative University Programs

- Duke University
- Texas A & M
- University of California
  - Scripps Institution of Oceanography
  - University of California at Berkeley
  - University of California at Davis
  - University of California at Irvine
  - University of California at Los Angeles
  - University of California at San Diego
  - University of California at Santa Barbara
- University of Miami
- University of Michigan
- University of Southern California
- University of Washington
- Woods Hole Institution of Oceanography

ABSTRACTS

The following abstracts were selected from the information bank of the Undersea Medical Society, as being relevant to this subject area.

ANONYMOUS.
Basic standard on way for commercial diving.
Triton 20:23; Jan./Feb. 1975.

The UK government's Training Services Agency has recently run a "Pilot basic underwater training course" with the purpose of setting a basic standard that will provide a framework for diving schools to build upon. Ten trainees went through 11 weeks of training in scuba, surface demand equipment, and standard hard-hat diving. Chamber operation, tool use, explosives and boat handling were included. Equipment of the Royal Navy was used, thus indicating a closing of the gap between RN and civilian diving techniques and training. A parallel move was the setting up of a Diving Training Center on the west coast of Scotland. (MFW/UMS)

ANONYMOUS.
Schools solve a diving problem.
Offshore 35:58-60; Mar. 1975.

The training program conducted by training director Bob Dykes at Taylor Diving and Salvage Co., Inc., consists of a diving training program, plus a program to train divers to become welders, and one to train welders to become divers. The latter has proved more successful. It takes an average of 18-24 months to qualify in the diving training program. Trainees must start with a certificate from a recognized diving school, then must pass a written test. They then go through a training period in a hyperbaric chamber with a 450-foot depth capability. They are then taught to fabricate umbilical lines, maintain compressor and hydraulic units, and perform other tasks of repair and maintenance. They then act as tenders during saturation dives, where they learn by doing. After three months, they qualify as tender-divers, and are permitted to dive to 150 feet. In another three months, they can, with the proper recommendations, qualify as Taylor divers. The welder-diver and diver-welder programs consist of 10 weeks of classroom and clinical training. Subjects are mixed gas diving equipment, saturation system theory and equipment, hyperbaric welding procedure, pipe alignment, and underwater habitat operation. There is also a two-week course to acquaint oil company representatives with diving problems and procedures. (MFW/UMS)

TRAINING S-11/ INDUSTRIAL LABORATORY GN-21

AQUADRO, C. F.
Examination and selection of personnel for work in underwater environment.
J. Occup. Med. 7:619-625; Dec. 1965.

Procedures and criteria for selection of underwater workers have been discussed. For comparative purposes, some considerations in selection of personnel for participation in other specialized programs in the foreign environments of space and the antarctic were presented. Three types of underwater workers were defined; these frequently may have a close interrelation. Nevertheless, the same individual may not necessarily perform well in each role. Past personal and work effectiveness, motivation, and physiological and psychological capacity to perform in a stressful and relatively unknown environment are important factors in determining suitability for successful underwater work. The compatability and continued effectiveness of the worker as a member of a group or crew is often as important as his individual capabilities. Cohesion of the group, particularly for prolonged periods in restricted quarters, is of considerable importance in effective team performance and successful accomplishment of its mission. (Author's summary)

BACHRACH, A. J.
Diving behavior.
In: Scripps Institute of Oceanography. Human performance and scuba diving. Proceedings of the symposium on underwater physiology, La Jolla, Calif., April 10-11, 1970, p.119-138. Chicago, The Athletic Institute, 1970.

The author summarizes some statistics on diving fatalities, pointing out the high number as compared with other dangerous activities such as skiing and sky diving. He then discusses some physiological factors. He notes that more emphasis should be placed on problems of hyperventilation and overdistension of the lungs. Since most deaths occur in shallow dives, decompression cannot be considered a major factor. Pulmonary barotrauma and air embolism, which are major causes of death, result from hyperventilation. Anxiety may trigger hyperventilation which brings on symptoms which further increase anxiety, resulting in panic. The author discusses the general problem of training at some length, suggesting that a more gradual approach be used in testing the diver in the ocean environment after preliminary training in the use of equipment in a pool. In the panel discussion following this paper, Capt. Behnke speaks of neurological damage following decompression, noting that lesions of the central nervous system tend to be permanent. In speaking of impairment in divers and other subjected to environmental stress, he lists criteria for selection, motivation, technical and professional competence, self-discipline, emotional stability. A table is presented listing intellectual, physiological and behavioral impairments which should disqualify a diver on any given day. Another table lists manifestations of acute and chronic fatigue: performance impairments, behavioral deterioration and physiological signs and symptoms. Dr. J. B. MacInnis contributes an interesting diagram describing the "diving performance corridor." The floor of the corridor consists of life support equipment and diving techniques. One wall is made up of the various aspects of the water environment; the other of aspects of the gaseous environment. The ceiling is the diver's physical and psychological condition. The corridor narrows with increasing depth. Dr. MacInnis also describes the shallow (30 ft) underwater habitat Sublimnos and recommends it as an effective training site. It is his belief that diver training programs would greatly benefit from the use of similar habitats, which are reasonable in cost ($20,000). (MFW/BSCP)

BERGHAGE, T. E.
The use of standard Navy classification test scores for the selection of diver first class candidates.
U. S. Navy Exp. Diving Unit, Rep. NEDU-20-72; 65 p. Aug. 15, 1972.

Training records at the Naval School of Diving and Salvage for the years 1965 to 1970 were surveyed. Four hundred and sixty-four complete records for diver first class students were found. These records were used to evaluate existing, readily available aptitude tests as predictors of success in diver training. Scores on the four subtests (GCT-General Classification test, MECH-Mechanical test, ARI-Arithmetic test, and CLER-Clerical test) of the standard Navy enlisted classification battery along with age were evaluated statistically. Results also indicate that even the best combination of scores on the Navy's standard classification test will only account for about 15 percent of the variance in trainee performance. (Author's abstract).

*TEST S-38/*SELECTION S-10/TRAINING S-11/APTITUDE BK-3/PREDICTION S-7/
PERFORMANCE BK-17/REPORT GN-12/FEDERAL LABORATORY GN-20/.

CABARROU, P.
Selecting divers by brain impulses.
In: Eaton, B., ed. The undersea challenge. Proceedings of the Second World Congress of Undersea Activities, p. 68-70. London, The British Sub-Aqua Club, 1963.

In previous studies it appeared possible to establish a relationship between the electroencephalogram (EEG) of a man at rest under atmospheric pressure and the aptitude of this subject for diving. In the work here reported, an EEG was taken at the start of the diver's course and a forecast was made of his potential value as a diver; marks were awarded for underwater performance and the results were compared with the forecast. Out of 154 pupils completing the course in 8 two-month courses, the forecast was accurate for 88 and wrong for 66. In each of the 8 courses, the 3 pupils with the lowest marks had been given an unfavorable forecast. The need is stressed for following a diver's career in order to find, if possible, an explanation for the failures in making accurate forecasts. Assessment of the EEG readings needs further study based on more experience. It is felt that the EEG is valuable in selecting divers. ((ART/BSCP).

CHARPY, J. P., J. P. Deyts and P. Wide.
Etude psychologique sur les travailleurs sous-marins a moyennes et grandes profondeurs.
(Psychological studies of underwater workers at medium and great depths)
In: Hesser, C. M. and D. Linnarsson eds. Proceedings of the first annual scientific meeting of the European Undersea Biomedical Society, Stockholm 13-15 June 1973. Forsvarsmedicin 9:452-458; July 1973.

The authors discuss variations of mood, problems of isolation, and of habitat habitability--The necessity for privacy and the need of social life. Psychometric studies of six subjects during three chamber dives of 50 to 62 ATA (Physalie V, Sagittaire II, and Physalie VI). In general, it is noted that variations in mental function were not systematic, since many interdependent factors were involved. As to sensory-motor function, however, a systematic diminution of performance was noted. Psychological examinations for selection are discussed. It is noted that individuals who may demonstrate slightly neurotic characteristics in normal life might better adapt to a career of diving and underwater work than those who seem better balanced. Psychological testing is still in the formative stage; actual criteria have not been established. (MFW/UMS)

COUSTEAU, J. M. and C. Millet.
Inner space: Man under the sea.
Architect. Des. 39:206; Apt. 1969

Here the authors are primarily concerned with the psychological and environmental problems of underwater habitats. The following are some of the factors which complicate life in the sea: thermal instability, excessive humidity, lack of space. Boredom must be combatted, as well as psychological difficulties resulting from lack of privacy. The increasing demand for undersea workers employed on a more or less continuous basis renders more and more important the need for the type of habitat that is designed with these problems particularly in mind. Distortion of the senses, lack of communication with the outside world, possible disruption of circadian rhythms, all contribute to the possible occurrence of psychological upsets. Some degree of comfort and privacy, and some provision for leisure activities must be provided. Architectural handling of the internal space of the habitat, in division of volumes, location of opening and flexibility of planning, can have an important effect on sensory perception; in brief, the underwater habitat must be humanized if the diver-worker is to operate effectively. (MFW/BSCP)

DEPPE, A. H.
A study of psychological factors relevant to the selection of scuba divers.
Univ. of South Africa. Ph.D. Thesis, 202 p. plus append. Jan. 1971

The study covers three related topics, viz. an analysis of psychological and psychophysiological factors affecting human performance in the diving context, prediction of success in a diver training course and prediction of success of adaptation in immersion. Four criterion factors were derived for the training course; these were diving skill, intellectual ability, task-orientation and emotional maturity. Multiple regression involving predictors and single criteria yielded weight validities ranging from .22 to .50. Sources of performance decrement in immersion were concluded to comprise sensory and motor restrictions, limitations in the method, speed and cost of underwater work, and psychological stress. Arguments are given to justify a model of underwater adaptation as centering on arousal and rate of information processing capacity. Hypotheses based on this model were not supported; nevertheless the results of experimentation gave a number of leads regarding arousal and cognitive performance in diving. Main conclusions are that arousal is largely a function of training methods, task-proficiency largely a function of spontaneous work-methods, and underwater cognitive performance primarily a consequence of available ability resources and the extent to which they are limited to arousal. (The appendix consists of glossary, a definition of job analysis factors, the assessment exercise by which senior divers rate trainers, the questionnaire on diving given to trainees, and a diver selection interview. The bibliography contains over 200 references.) (Author's summary)

*PSYCHOLOGICAL FACTORS BK-18/*SELECTION S-10/TRAINING S-11/MENTAL FUNCTION BK-12/PERFORMANCE BK-17/ADAPTATION P-50/MOTIVATION BK-13/AROUSAL BK-4/TESTS S-38/QUESTIONNAIRE S-8/THESIS GN-11/NON U.S. GN-43/PREDICTION S-7

DEPPE, A. H.
Performance criteria in diver training.
Percept. Mot. Skills 32:718; June 1971.

Using a sample of 71 male diver trainees from scuba diving courses, a study was made of 29 behavioral elements, positively and negatively defined. Instructors reported on their own students, and these data were converted to standard scores, which were "subjected to iterative principal factor analysis followed by varimax rotation to simple structure." The four factors which emerged were diving skill, intellectual ability, task-orientation and emotional maturity. It is noted that social compatibility is apparently unimportant; in fact, it is probable that the successful diver would be the type who would shun social activity. Underwater performance and invulnerability to stress are grouped under one factor. (MFW/BSCP)

*PERFORMANCE BK-17/*TRAINING S-11/SELECTION S-10/NON U.S. GN-43/BEHAVIOR BK-5

EGSTROM, G. H. and A. J. Bachrach
Diver panic
Skin Diver 20:36-39; Nov. 1971

It is stated that many, if not the majority, of diving fatalities result from panic, which results from the realization that one has lost control of the situation. Training methods can be designed so as to make this loss of control unlikely. It is most important to give instruction step by step, proceeding very gradually. The diver thus forms the habit of competing with himself and his environment rather than with other divers. By "overlearning" diving techniques and the use of his equipment, his capabilities become as automatic as the act of walking. It is advisable to give the student diver tasks to perform underwater as soon as he is sufficiently proficient in the use of his equipment. Productive activity is most helpful in controlling panic. Various indications that the diver is becoming over anxious are: constant checking of equipment, frequent glances to the surface, and, most important, irregularity of breathing. This can result in hyperventilation, which can result in loss of consciousness and drowning. There is a possibility that raising the blood sugar level before diving would be desirable, since there seems to be a similarity of symptoms of hyperventilation and low blood sugar. Another serious problem related to panic and to breathing, is the severe danger of holding the breath while ascending. Another effect of stress is the narrowing of peripheral perception. One of the first things a diver in trouble should do is to ditch his weight belt. In many instances of drowning, the victim is found wearing his weight belt, and with an uninflated vest. It is important at all times to be on the lookout for symptoms of anxiety or undue stress in one's self and in others, and to avoid or prevent diving in these conditions.

The diver who is afraid to admit his apprehension and who is concerned chiefly with maintaining his image is a danger to himself and to others. (MFW/BSCP)

FLEMMING, N. C.
Diver training and education.
In: Diving applications in marine research.
Proceedings of a seminar, National Institute of Oceanography, Godalming, Surrey, U. K.,
December 1971, p. 136-167. Published by the Institute. 1972.

Physical, medical, and psychological tests reveal that divers do not differ significantly from the average for the population, apart from their being rather fitter. This makes it very difficult to identify the qualities which make a good diver. Selection and training of divers is compared with that for RAF and airline pilots in order to examine testing methods and the possible causes of the high failure rate which is normal on diving courses. In spite of the superficial similarity between the combination of physical and intellectual skills in diving and flying, it is harder to predict the success of diving trainees than flying trainees, and failure rates of 35% are experienced in diving compared with 20-30% in flying. A notable behavioural difference on the courses is that pilots fail in examinations or tests set by their instructors, while divers tend to drop out voluntarily. This is clearly related to the discomfort and danger of diving, and it is difficult to design short selection tests which will predict whether a trainee will be able to endure repeated discomfort. The discrepancy between the apparently average qualities of divers and their actual rarity may be accounted for by assuming that they require to combine certain qualities which are on the average negatively correlated in the population as a whole. Consideration is given to the question of training research personnel to dive, and the problem of maintaining their diving standards with minimum interference to their normal work. Where routine working diving is not involved, and where frequent practice dives are not feasible or convenient, it is recommended that the divers engaged in a given diving project should undergo a series of work-up practice dives tailored to the work project, and taking account of the time-lapse since previous diving. (Author's abstract)

TRAINING S-11/EDUCATION S-3/SELECTION S-10/PSYCHOLOGICAL FACTORS BK-18/ PHYSICAL FITNESS R-11/UK GN-44/PROCEEDINGS GN-9

GUNDERSON, E. E. K., R. H. Rahe and R. J. Arthur,
Prediction of performance in stressful underwater demolition training.
J. Appl. Psychol. 56(5):430-432, 1972.

The relevance of selected biographical, physical fitness, and health status measures for success in Underwater Demolition Team training was investigated. A combination of five variables, including a Cornell Medical Index subscale, yielded highly significant cross-validity coefficients with training success. Physical fitness tests were the most important predictors of training success, but prediction also could be enhanced by assessing physical and emotional health status with questionnaire methods. (Author's abstract)

HELMREICH, R.
Characteristics of the aquanauts.
In: Miller, J. W., J. G. Van Derwalker, and R. A. Waller, eds.
Tektite 2: Scientists-in-the-sea, p. VIII-28-29. Washington, D.C., U.S. Department of the Interior, August 1971.

The aquanauts, as a group, formed a highly qualified and educated population. There were, however, large individual differences in experience and in personality characteristics. In this section, descriptive statistics from the Aquanaut Background Questionnaire and other pre-dive measures are presented to provide an indication of the characteristics of the research group and to show the range of variation present...The Allport-Vernon-Lindzey Study of Values (Allport, Vernon and Lindzey, 1960) is a widely used test which measures the relative strength of six major value areas (theoretical, economic, aesthetic, social, political, and religious)....the profiles for Tektite scientists and Sea Lab II civilian aquanauts as well as Mt. Everest explorers are almost identical. Scientists undertaking hazardous but professionally rewarding tasks seem to have a similar constellation of values characterized by high theoretical and aesthetic values, low religious values, and average social, economic, and political concerns. Although teams do not differ significantly on background variables, recorded events during childhood and youth are significantly related to individual performance and adjustment underwater. These are discussed. (Author)

TESTS S-38/QUESTIONNAIRE S-8/SELECTION S-10/HABITAT Y-13/UNIVERSITY LABORATORY GN-2/PSYCHOLOGICAL FACTORS BK-18/BOOK GN-3

HELMREICH, R., J. Wilhelm and R. Bakeman.
Prediction of in-habitat behavior.
In: Miller, J. W., J. G. Van Derwalker and R. A. Waller, eds.
Tektite 2: Scientists-in-the-sea, p. VIII-30 - VIII-59, Washington, D.C. U.S. Department of the Interior, August 1971.

The author discusses the "effectiveness of pre-mission predictive variables in accounting for the actual behavior recorded" during the various missions of Tektite 2. The availability of "continuous, objective, behavioral criteria" makes Tektite 2 a particularly valuable source for the evaluation of predictive measures of performance and adjustment. The principal predictive tool used was the Life History Questionnaire (LHQ), which covered the first 18 years of life. In this discussion, the LHQ variables are related to the criterion of total marine science achievement during the mission. In a very general analysis of the data, it is concluded that members of small families, from small towns, of lower social status, with little religious background or education, and with good academic performance in the elementary grades, tend to become the most effective marine scientists. It was found that first-borns out-performed later-borns, in contrast to findings in Sea Lab. This is explained by the fact that stress was much greater in

Sea Lab; where stress is not a factor, first-and only-borns tend to out perform later-borns. Poor health in childhood, followed by heightened physical activity in the teenage years is a characteristic of the top performers. The results of the observations made with the aquanauts, and those made with a very different group of U. S. Navy enlisted men show that certain variables relate to performance in the same degree. It is concluded that the LHQ is a most effective predictive test, applicable both to research into the antecedents of behavior and into selection of candidates for specialized roles. (MFW/BSCP)

**PREDICTION S-7*BEHAVIOR BK-5/*HABITAT Y-13/SELECTION S-10/QUESTIONNAIRE S-8/PERFORMANCE BK-17/PSYCHOLOGICAL FACTORS BK-18/BOOK GN-3/UNIVERSITY LABORATORY GN-22

KINNAMAN, P. V.
A school for diving.
Mar. Technol. Soc. J. 8:18-20; June 1974.

Highline Community College in Midway, Washington has been developing a diving school over the past seven years with the help of Sea Grant awards. The school is located at Redondo, Washington, on Puget Sound. It consists of a two-year diving technician curriculum, which can be tailored to meet individual needs. The first year is devoted to classroom training. In the second year training is given in the use of all types of diving equipment from the hard-hat Mark V to the more recent types of wet suits. The older type of equipment is still used in some locales, and hard-hat experience is a desirable asset. Use of underwater power tools is taught. The school also makes use of a diving bell; this type of diving is becoming more widely used commercially. The chief purpose of the school is to train divers and then to place them in jobs. About 15 students complete the course each year; most of these have been placed. (MFW/UMS)

KOTASKOVA, J.
Some psychological aspects of isolation in hyperbaric conditions.
Rev. Physiol. Subaquatique Med. Hyperbare 2(1):20-23; 1970.

During isolated deep dives, many accidents are brought on by psycho-physiological disorders (euphoria, perception disturbances, etc.) Phenomena of sensory impairment, both visual and auditory, increased by lack of external stimuli, result from prolonged subjection to a hyperbaric atmosphere. Behavior of subjects isolated and exposed to hyperpressures for long periods (three days or more), with or without external stimuli transmitted through the acoustic canal, has been studied by the author. The greater part of perception disorders (hallucinations and pseudo-hallucinations) occur in the night or early in the morning, when there are no external auditory stimuli. Reactions vary greatly from one subject to another. Identical phenomena may be observed in different circumstances during high altitude solo flights or with cosmonauts. Psychological difficulties, such as personal hostilities, that arise when a small group of men live together in an environment of sensory deprivation and isolation, as in a hyperbaric chamber, are briefly discussed. It is noted that the great difference between model conditions and natural conditions in their psychological impact make investigation in this field difficult. Further work is planned, however, with an effort made to allow for these discrepancies as well as for individual differences between the subjects involved. (Author's abstract expanded by MFW/BSCP)

NICHOLS, A. K.
The personality of divers (and other sportsmen)
In: Lythgoe, J. N. and E. A. Drew, eds. Underwater Association Report 1969. p. 62-66. Guildford, England, Iliffe Science and Technology Publications, Ltd.

The 16 PFQ (16 personality factor questionnaire developed by Cattell (1962)) was administered to one hundred sub-aqua divers in the North of England. Significant differences from the general population were found on nine of the first-order factors, generally in the direction to be expected from participants in sport. Second-order factors did not show any great deviation from the mean. The group was divided according to length of diving experience. The more experienced divers were not significantly different from the less experienced divers on any factor, but tended overall to obtain less extreme scores. The diving group showed a higher coefficient of similarity with swimmers than with climbers. It is suggested thus that interest in diving may more often evolve from an interest in swimming than interest in outdoor pursuits. (Author's abstract)

PARKER, D. W.
The hazards of SCUBA diving.
Can. J. Public Health 56(7):292-296; 1965.

Regarding skin and SCUBA diving, it is felt to be essential that the public be indoctrinated in the need for instruction on the difference between safe and unsafe equipment, and the hazards faced by untrained divers. The safety requirements for masks, fins, snorkels, tanks, regulators, and straps, are enumerated. It is stated that faulty equipment is the greatest single cause of diving accidents. The physical laws governing related subjects such as gas compressibility (Boyle's Law), Dalton's Law of Partial Pressures, Henry's Law regarding the solubility of gas in liquid, are explained in connection with diving hazards such as air embolism, oxygen poisoning, nitrogen narcosis and "squeeze" affecting various parts of the Other dangers that may lead to fatalities are air starvation (a result of overexertion, which can bring on fatal panic), seasickness (vomiting while wearing SCUBA equipment can cause death), shallow breathing (this can cause a dangerous build-up of CO_2, and also may permit the diver to stay under for so long a period that he does not have enough air left for decompression), decompression sickness, expansion of gas in stomach and intestines, (intake of gas-producing foods and liquids before diving should be avoided), carbon dioxide poisoning caused by excessively long submergence by skin divers. A list of recompression chambers located in Canada and northern New York state is appended. (MFW/BSCP)

ROSS, H. E.
Personality of student divers.
In: Lythgoe, J. N. and J. D. Woods, eds., Underwater Association Report 1968, p. 59-62. Published by the Association.

Aqualung diving in the universities is carried out both as a sport and as a tool for scientific enquiry. It is interesting to know what type of student takes up diving, and whether there are any useful criteria for predicting success at diving. An investigation was therefore made of the students who joined the Hull University Underwater Club during the past two years...Any personality variables which might distinguish the university diver from the normal population are probably due to his being an intelligent male scientist. As a physical sport, diving has little to recommend it (at least in British waters). Unless the diver is interested in some underwater activity such as photography or observing marine life, he will quickly become bored. Underwater projects are necessarily of a scientific or semi-scientific nature. The artsman tends to have fewer skills than the scientist, and often finds himself acting as the unpaid research assistant of a scientific friend. It is not surprising that nonscientists usually drop out. (Author)

SALZMAN, W. L.
The hazards of SCUBA diving.
G. P. 26:98-104; 1962.

The SCUBA contains a pressurized air source that compensates for the increased water pressure at depth by increasing the breathing air pressure. Thus, the alveoli remain at their normal size. The path-physiology of diving depends largely on the divers' ability or inability to properly equalize air pressure in body cavities and equipment with the surrounding water pressures. Candidates for this sport must have physical and psychological qualities certified as suitable by the informed physician. The best age for divers has been found to be between 20 and 30. Panic is the diver's greatest danger, and the psychologic makeup of the diver should be relatively stable. (Author's summary)

SMUSSEN, J. E.
Man in isolation and confinement.
Chicago, Aldine Publishing Co., 1973.

Some of the research presented (The work of Radloff, Haythorn and Altman) was actually conducted in an undersea environment. The book as a whole has application to this area of activity in that it deals with the ability of man to cope with sensory, perceptual, and social stress arising from an abnormal environment. In particular, studies dealing with sensory deprivation (Zubek) and biological rhythms (Fraisse) are relevant. The emphasis is social-psychological rather than biomedical, with much attention given to selection criteria both for individuals and for groups with relation to satisfactory performance in confined and isolated environments. (MFW/UMS from review by P. D. Nelson in Undersea Biomed. Res. 1:114-115; Mar. 1974)

*ISOLATION BK-10/*CONFINEMENT BK-7/PSYCHOLOGICAL FACTORS BK-18/SENSORY DEPRIVATION BK-44/BIOLOGICAL RHYTHMS R-4/SELECTION S-10/BEHAVIOR BK-5/PERFORMANCE BK-17/BOOK GN-3

SOMERS, L. H.
Selection and training of aquanauts for Hydro-Lab type saturation dives.
Hydro-Lab J. 2(1):97-103; 1973.

Professionally supervised saturation dives at a depth of approximately 50 feet may be successfully and safely undertaken by scientist-divers of limited diving backgrounds. Elaborate aquanaut selection criteria are not deemed necessary for shallow, short-duration saturation dives. In most cases, scientist-divers who have received high-quality basic scuba diver training and acquired a reasonable amount of diving experience, 50 dives or more under all conditions, perform safely and satisfactorily. The diver must be medically qualified and in fairly good physical condition. Personal psychological conditioning to overcome the natural instinct of surfacing in an emergency is probably the most important aspect of individual preparation. A 3-5 day period of habitat and seafloor orientation diving prior to saturation is deemed necessary. (Author's abstract)

*SELECTION S-10/*TRAINING S-11/SATURATION DIVING S-73/UNIVERSITY LABORATORY GN-22

TATARELLI, G.
Problimi psicologici nella sicurezza subacquea.
(Psychological problems of underwater environment.)
Med. Sport 21:261-264; July 1968.

The general and peculiar aspects of underwater environment are examined in order to outline a standard psychological profile of the (diver); the psychological tests and the most useful criteria of selection are also sketched. Eventually the problems related to age and sex of the (diver), from the psychological point of view are discussed. (English summary)

VROEGOP, P.
Psychodiagnostic selection of divers: study review, 1972.
Netherlands, Hilversum Diving Medical Center, Jan. 1973.
(NAVSHIPS transl. 1416)

A program of more careful psychodiagnostic examination of diver-training candidates was inaugurated in 1967, since which time the training results have greatly improved. The effectiveness of the program is demonstrated in a diagram, which shows that after the inauguration of these examinations there was a much higher percentage of rejections as well as a lower percentage of drop-outs and a high percentage of candidates successfully completing training. Age was found to be an important factor also, in that divers near the maximum age limit (28 for diver officers and 24 for divers) underwent training more successfully. Examination included interviews, careful survey of the anamnesis, and various questionnaires and tests, the nature of which is not made very clear in this report. (MFW/SCD)

WELTMAN, G., R. A. Christianson and G. H. Egstrom
Effect of environment and experience on underwater work performance.
Hum. Factors 12(6):587-598; 1970.

Five experienced divers and 15 novice diver completed a complex underwater assembly task and sets of written problems in a water-filled tank and in the ocean. Performance measurements included subtask completion times, problem-solving accuracy, activity analysis, and basic physiological variables. Experienced divers showed essentially unchanged performance between tank and ocean. Novice divers performed slower than the experienced divers in the tank and showed a marked decrement in both assembly time and problem-solving accuracy in the ocean. The results suggest that diving experience improves underwater motor skills rather than work strategy, and that psychological stress was a significant factor even at shallow ocean depths for novices. (©BA)

COGNITIVE AND PSYCHOMOTOR PERFORMANCE

Part #6 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Glen H. Egstrom, Ph.D. (Chairman)
Director, Underwater Kinesiology Laboratory
University of California
Los Angeles, California

Arthur J. Bachrach, Ph.D.
Chairman, Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, Maryland

Dorothy E. Fletcher, Ph.D.
Institute for Environmental Medicine
University of Pennsylvania
Philadelphia, Pennsylvania

W. S. Vaughan, Jr., Ph.D.
President, Oceanautics, Inc.
Landover, Maryland

COGNITIVE AND PSYCHOMOTOR PERFORMANCE

Part #6 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Glen H. Egstrom, Ph.D. (Chairman)
Director, Underwater Kinesiology Laboratory
University of California
Los Angeles, California

Arthur J. Bachrach, Ph.D.
Chairman, Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, Maryland

Dorothy E. Fletcher, Ph.D.
Institute for Environmental Medicine
University of Pennsylvania
Philadelphia, Pennsylvania

W. S. Vaughan, Jr., Ph.D.
President, Oceanautics, Inc.
Landover, Maryland

TABLE OF CONTENTS and Organization for part 6

Cognitive and Psychomotor Performance

I. SENSORY AND PERCEPTUAL PROCESSES 1

A. Visual

1. Visual Fields
2. Acuity
3. Distance Perception
4. Color Perception

B. Auditory

C. Tactile

D. Spatial Orientation

II. COGNITIVE PROCESSES 3

A. Surveillance

B. Short-term Information Retrieval

C. Long-term Information Retrieval

D. Information Processing Facility

E. Decision Making, Problem Solving

F. Assigning Priorities, Selecting Strategies

III. PSYCHOMOTOR PROCESSES 8

A. Physical Working Capacity

IV. RECOMMENDATIONS 12

V. LABORATORIES 13

APPENDIX A 15

APPENDIX B 19

Knowledge about underwater work performance dimensions is largely derived from laboratory research, rather than from data obtained from the actual performance of operational divers. This fact, coupled with the tendency to set up laboratory experiments based on discrete phenomena under controlled conditions, rather than making functional studies under field conditions, has resulted in findings which are difficult to interpret. This panel has attempted to restrict its focus to those phenomena which appear to impinge on diving safety and underwater work effectiveness. The extensive literature has been reviewed and interpreted to reflect our impression of the state of the art and implications for safe, effective diving. Some of the references have been included in this report because they contain references to other studies which are pertinent to our subject.

The underwater worker must rely on an external life-support system to transport him to the underwater work site, where he must perform under a variety of highly specific performance constraints. These constraints include diminished sensory and perceptual capabilities, interference with cognitive processes and psychomotor skills, and reduced physical working capacity. Factors such as environmental, psychologic, and/or physiologic stress, inappropriate human engineering efforts, and inadequate selection and training programs further hamper the diver's efforts. Little systematic study of the interaction of these variables has been conducted; as a result, the accurate prediction of performance decrements for a given set of diving conditions is virtually impossible to make at this time.

The underwater worker must make highly specific adaptations to his equipment, his environmental working conditions, the work strategies he uses to do the job, and the stresses which reduce his effectiveness. The diver's ability to adapt must be sufficient to allow him to cope with these constraints and still produce effective work in a safe manner. It is probable that a great many diving accidents result from inadequate knowledge of cognitive and psychomotor limitations; calculated risks are therefore inaccurately assessed. The consequences of this error may range from increased operating time to failure or an accident.

I. SENSORY AND PERCEPTUAL PROCESSES

Exposure to the complex conditions of the underwater work environment has myriad effects on man's basic sensory and perceptual processes. These relationships have been detailed in the large and growing research literature and summarized in recent review articles and books (1, 3, 43). This section will highlight those few relationships which are of clear and direct relevance to diver safety. Sensory and perceptual problems are identified, and potential solutions suggested.

A. Visual

1. Visual Fields

The diver's visual field is severely restricted compared to that of workers in air environments. Distance vision is limited by the turbidity of the water, and peripheral vision is limited both by the physical design of the facemask and by the distortion of light as it passes from water to air at the faceplate (48, 42). In addition, the diver's attention is generally focused on the task, so that vision becomes an unreliable means for detecting potential hazards. Means other than visual for providing warning information to a working diver should be explored.

2. Acuity

Objects within the diver's visual field are not easily discriminated. Fine detail tends to be blurred by the scattering effects of turbidity in the water (36). In very clear water and in good conditions of illumination, objects appear larger than their actual size in air. The working diver, however, is rarely in clear water, and safety-related devices, signals, and so on, should be oversized to ensure detection and legibility.

3. Distance Perception

One optical effect of vision through a faceplate is the production of an image of an object which appears to be 3/4 of its actual distance away (35). The consequence of this phenomenon is that the diver is inclined to underreach. He sees an object, reaches for it and misses to the near side. Tasks involving precise hand-eye coordination are potentially affected by this effect, and safety-related devices should be designed for a gross level of performance.

4. Color Perception

Water selectively absorbs light energy by wavelength so that the composition of ambient light from the surface depends on depth. At very shallow depths all wavelengths are represented except those associated with the perception of red. As depth increases, the oranges, yellows, greens, and blues are progressively absorbed. Differences in turbidity of the water complicate this orderly progression by scattering light energy in a different manner (52). Small-sized particles scatter light of short wavelength (blues and greens) more than that of longer wavelengths (reds and oranges). Larger-sized particles tend to scatter all wavelengths equally. Consequently, the perception of natural light in a given body of water will depend on water turbidity and the diver's working depth. If natural light from the surface is used for illumination, the perceived color of underwater labels or controls will change with the depth and the turbidity of a specific body of water. This phenomenon argues against the use of color for coding in general, and particularly when the code is essential to diver safety.

B. Auditory

Underwater sound is omnidirectional; bone conduction of sound is the principal means of perception underwater (1). Consequently, the diver's ability to locate sound sources is poorer in water than in air, and the diver cannot be expected to avoid hazards on the basis of auditory signals.

C. Tactile

Touch sensitivity of the skin is gradually reduced by exposure to cold water; it is severely limited when skin temperature becomes $8^{o}C$ or less (39). Cold hands are part of the working conditions of diving, and the design of safety mechanisms should take reduced sensitivity, particularly of the fingers, into account. For example, shape codes on safety controls should be designed for whole-hand rather than finger discrimination (Appendix B).

D. Spatial Orientation

The diver's ability to orient himself spatially underwater is lessened by the homogeneity of the visual field with its lack of reference points; there are typically few fixed and distinguishing features within his range of visibility (42). The free-swimming diver has the additional problem of approximate weightlessness in the water combined with a degraded capacity to orient himself in relation to the vertical dimension of his environment (40). To ensure diver safety, provisions to minimize the diver's vulnerability to becoming lost and disoriented should be made.

II. COGNITIVE PROCESSES

Impairment of the diver's cognitive processes has been considered a serious threat to diving safety and efficiency since Green (29) noted impairment of judgment when breathing hyperbaric air, and Behnke, Thomson, and Motley (12) attributed difficulty in concentration, increased arithmetic errors, and a tendency to idea fixation to the increased partial pressure of nitrogen. This research has been energetically extended to a wider range of stressors found in various hyperbaric environments, including types of inert gas, depth, compression rate, duration, cold, underwater optics and acoustics, CO_2, O_2, equipment, work load, condition of the diver, isolation, confinement, apprehension, and so forth. Despite this body of literature, we can at present only make preliminary predictions about the kind and degree of cognitive change to expect in a particular diving mode. We can be even less confident in predicting whether or not cognitive changes will be critical to the diver's efficiency and safety underwater when compared to changes in sensation, perception, psychomotor performance, or work capacity.

Biersner (16) has suggested that cognitive processes may be less affected than psychomotor tasks in deep helium-oxygen dives, and more affected in shallow hyperbaric air dives. In some studies (34) more complex tasks appear to be more affected. Current reviews of human underwater performance by Adolfson and Berghage (1), Bennett (15) and Bachrach (3), and Shilling, Werts, and Schandelmeier (43) point to the difficulty in comparing these different experiments. Members of a recent workshop (4) agreed that comparisons among future studies would be facilitated by the standardization of performance testing methods. The workshop also noted that such methodological refinement would only be useful if the tests accurately reflect the actual work of the diver. These methods are beginning to be used, but they are not yet widespread. We must therefore still depend on the available literature for a general description of the cognitive aspects which could possibly be critical to the diver's safety and efficiency.

The cognitive aspects of performance include surveillance, information retrieval, information processing, and decision making. For any single completed act, these cognitive steps begin with sensory and perceptual processes, and are followed by psychomotor processes; work capacity modifies the output or action (23). Factor analysis has more or less reliably identified more discrete kinds of cognition within these broader categories (4, 22, 30). These categories have been used in selecting individual lists for possible inclusion in standardized underwater test batteries, and have also loosely guided the selection of problems in this discussion. However, until the test batteries derived from factor analysis are used extensively, it is not possible to determine whether or not these factorially distinct tasks remain distinct or unique in underwater performance. Factors obtained in controlled laboratory tests which depend on artificial procedures may exaggerate one step in the flow of processes from receipt of information to performing the action, while the complexity of the task may make many steps important in the real underwater world (3). Closer cooperation between researchers and diving operators is essential to relate laboratory parameters to those of actual diving operations more closely (47). In particular, a detailed task analysis of the specific work involved in operational diving is needed.

A. Surveillance

Beyond direct sensation and perception, the diver must search out or remain alert to additional information that will improve his decision making, and thus his safety and efficiency. The diver needs to develop an awareness of cues, and he must learn the techniques of observing environmental events as well as his own behavior. For example, he must remain vigilant to infrequent events for long periods or he must simultaneously monitor a wide range of status indications to note a change in the status of any indicator. These tasks must be time-shared with the continuous task of attending to his life-support system.

Time-sharing tests indicate that cold water impairs attention to a randomly repeated stimulus during the performance of a continuous task such as manual tracking (21) or mental arithmetic (44). However, cold water did not systematically affect time-sharing when the detection stimulus was either a choice reaction time signal, monitored while the diver continuously controlled the vehicle's depth and heading, (46) or a peripheral light, while the diver performed an assembly task (27).

These results illustrate the difficulty in dealing with complex task design. For so subtle a concept as time-sharing, we need a clear reference test which could be used to elucidate the psychological parameters of new tests designed to simulate a real work situation.

Transferring the complex task to the real environment, where stressors are even more complex, can further confound data interpretation. In a simulated chamber pressurization, Weltman, Christianson, and Egstrom (49) found that time-sharing scores decreased because of apprehension; apprehension was also verified by increased heart rate and self-reports of increasingly anxious moods. To separate such effects from the systematic relationships between a potential stressor and a cognitive ability, Dickson, Lambertsen, and Cassils (24) recommend testing the stressor, to the degree that safety permits, through the entire range of its effect.

Studies agree that vigilance is reduced as a function of pressure for relatively narcotic gases such as nitrogen; however, reduction of vigilance is minimal for the less narcotic gases, such as helium or neon (31). In fast compression using oxygen-helium, Bennett (14) noted reduced vigilance, and suggested that vigilance may be a symptom of a compression syndrome as distinguished from the High Pressure Nervous Syndrome.

B. Short-term Information Retrieval

For the relatively isolated diver, the ability to retrieve information from memory may be vital to safety and efficiency. Memory appears to be a higher-order ability, distinct from other cognitive abilities, but involved in a wide variety of tasks (22). In one experiment, short-term memory loss associated with fatigue appeared after about ten hours (17). Cold affects immediate memory in some studies (47) but not in others (19). Again, different tests which ostensibly test the same ability produce different results.

C. Long-term Information Retrieval

The often observed post-dive forgetting of events which occurred during the dive was demonstrated by Egstrom et al. (27) in a test of post-dive recall of material studied underwater. The same investigators also tested the equally important task of remembering associations learned during the dive. Recall was better than recognition for cold water in both cases but the two types of memory retrieval did not differ for warm water dives. This result suggests that job check lists for recall of underwater operating procedures and post-dive symptom check lists for debriefing may be valuable. It should be stressed that memory is a crucial diving skill; accurate reporting is essential in the field. Diving contractors often complain that divers are not accurate. Such inaccuracies are not deliberate or careless, but are probably the result of memory impairment.

Wide variations in the design of associative memory tests may explain the disagreement among researchers as to whether or not there is a significant effect of high-pressure normoxic helium on long-term information retrieval. An apparent effect of helium on long-term memory may be attributed to apprehension (18, 41). Narcotic gases, however, are usually found to affect associative memory (24).

D. Information Processing Facility

Facility in manipulating cognitive elements such as numerals, symbols, or words, according to simple or well-learned operations may represent a large part of the so-called higher mental processes. Research has concentrated on this type of test because of its practicality in the laboratory. The digit-symbol, simple arithmetic, and word association tests are examples. These information-processing tests are considerably affected by narcosis. A majority of the research has found little effect at high pressure with normoxic helium-breathing, except that Bennett (13) reported considerable and progressive decrement to 15 ATA. Processing more complex symbol relationships, as in a verbal comprehension test, appears to be less susceptible to narcotic effect (11).

E. Decision Making, Problem Solving

Higher-order cognitive abilities have been thinly represented in the literature. Bowen (19) and Vaughan and Andersen (46) have studied symbol processing, map problem solving, and navigation problems. Cold water appears to have only a distracting effect on producing omitted test items, rather than a systematic effect upon time and accuracy scores. Kiessling and Maag (34) found that narcosis at 4 ATA degraded performance on the Gottschaldt symbol test. Dickson, Lambertsen, and Cassils (24) reported decreased performances in inductive ability with increasing nitrous oxide concentrations at sea level. Scores on a navigation problems test decreased with exposure time but not with cold (46).

F. Assigning Priorities, Selecting Strategies

It is generally assumed that divers use the same work strategies when performing standard tasks. Individual divers do tend, however, to develop unique ways of approaching a specific task, and this use of individual variation often proves advantageous. A diver may also change his customary strategy under pressure of an increased work load. Individual diver characteristics, such as experience, intelligence, and motivation, may increase the skill with which an individual diver handles strategies in his work. Divers trained at different schools or at different locations do develop procedures common to their groups. Working strategies developed on one diving system hinder the diver's ability to adapt to a new work environment, particularly if the old techniques are inappropriate to the new set of conditions. The lack of standardized operating procedures for a particular system and task is a factor which contributes to this problem, as does inadequate training or lack of awareness of task/situation specificity.

As a member of a high-risk (and presumably high-gain) occupation, the diver is relied upon to be a competent and confident underwater performer. The conditions of stress which accompany underwater work may impair the diver's ability for self-evaluation. Although divers may be inaccurate when reporting on their own condition, perhaps to protect their reputations as effective divers, (17, 25), their sensory systems are the most accurate sources of physiological data. Training divers to report on stress-related health conditions would yield invaluable safety information (7). To systematize diver reporting, brief symptom and mood check lists might be used periodically to keep supervisors aware of the diver's condition. Biersner (17) found that divers are willing to report changes in mood; these reports could serve as early indicators of severe fatigue, which divers are often unwilling to report directly.

Underwater work is a complex task which requires that the diver divide his attention among several pressing jobs. First priority must be given to his life-support system, without which he could not survive. Environmental hazards, such as marine hazards and current are distractions which further interfere with his work. Equipment and tool problems also interfere with optimal performance. Strategies for handling divided-attention tasks have been discussed by Miller (38) and by Fitts and Posner (28) and applied to diving in a discussion by Bachrach (3). A diver in a divided-attention situation must assign priorities, i.e., select those aspects of the task which need immediate attention, while assigning a lower priority to others. The choice of strategies may also include eliminating certain tasks, or allowing performance errors to increase in the interest of time. Time on the bottom, particularly in decompression dives, contributes heavily to the diver's problems in a divided-attention task. The time-sharing strategies of divers should be analyzed in assessing task performance.

III. PSYCHOMOTOR PROCESSES

The ability to manipulate controls, mechanical parts, and assemblies is crucial for the diver in underwater work. Studies of dexterity generally differentiate between finger dexterity, which involves the coordination of finger movements in performing fine manipulations such as grasping, placing, and assembling small objects (43), and manual dexterity, which is examined in tests involving the whole hand, rather than the fingers only. Manual dexterity is the ability to make arm-hand movements in a skillful fashion. This difference between finger and manual dexterity is referred to in several contexts dealing with underwater performance (3). Tasks of both abilities have been widely used; Vaughan points out, however that though these tests are well established and standardized, they have been used primarily in hyperbaric chambers. Tests used in the few studies done in the open sea tend to be simplified adaptations, of uncertain validity and reliability, of the standardized tests. Nevertheless, it is apparent from the studies done (10) that dexterity is affected by cold water and the diver's protective equipment, particularly his gloves, which make fine manipulations and discrete motions, such as manipulating small controls, difficult if not impossible.

Assembly tests (43) are distinguished from dexterity tests in that they include components which go beyond the simple manipulation of small objects. These assembly tasks usually have practical validity as in the case of the UCLA pipe puzzle (50) and the task used by MacInnis (37), both of which are complex assemblies involving varying numbers of pipe valves, connectors, and flanges. A simple assembly task such as the one developed by Bowen et al. (20) for use in the water during SEALAB II, included 1-ft lengths of pipe which were joined together by nut, bolt, and washer assemblies. A simple assembly task applicable to the diving situation is the Tooker Patch task; this test was used as part of an assessment of diving systems (2). The test features a patch used in salvage operations for plugging portholes or small holes in vessel hulls; it is designed for quick one-or-two man assemblies on the outside of the ship. On this test, factors such as cold appear to degrade performance in both simple and complex assembly, but performance of complex tasks is affected to a greater degree. Another factor which interferes with safe and effective performance in complex assemblies is the protective equipment used by the diver, especially equipment which limits his mobility.

Multilimb coordination is another important feature of diver psychomotor performance; the use of arms, hands, legs, and feet is essential to completing the task. Divers frequently use legs and feet to kick umbilicals aside to achieve greater mobility while performing a task. Limb coordination can be impaired by the diving suit and the loss of flexibility.

Arm-hand steadiness is another important psychomotor aspect of diver performance, particularly at greater depths. It has been studied primarily in hyperbaric chambers to depths as deep as 51 ATA. Tremor may seriously interfere with diver performance at depth, and it is an important symptom of what has been called the High Pressure Nervous Syndrome (5, 6, 32). Many factors are implicated in the development of the High Pressure Nervous Syndrome, such as compression rate.*

The diver's ability to communicate with other divers working in the water as well as topside is central to his efficiency. There are many obstacles to effective inter-diver communication, including the well known problem of helium speech. Though unscramblers have proved effective in many situations, particularly in chamber operations, adequate communication among the parties involved in an operational dive remains a problem. Misinterpretation of working messages occurs in the transmission of information; this can be detrimental to the operation as well as hazardous to the diver underwater. Mask and communication systems design and a signal-to-noise ratio which is unfavorable to diver-topside or diver-diver communication are among the factors which contribute to transmission problems. Message content is another problem, particularly in emergency situations. The lack of standardized message coding, which has been used in pilot communication, presents an operational problem in diving.

In situations where transmission and reception are inadequate, interpretation is a major problem. The necessity for repetition often delays action and requires excess effort. Variation of communication procedures and the training of divers and tending personnel contribute to this problem, as do certain inadequacies in equipment.

The diver's inability to move his jaw freely when speaking, a result of movement limitations imposed by some masks, poses a major problem in equipment design. The diver's effort to overcome the obstacles imposed by mask design induces fatigue, and further limits the diver's ability to articulate effectively.

A. Physical Working Capacity

The physical working capacity of divers appears to be modified significantly as a result of variables such as equipment design, fitness level, and environmental factors, including the water medium, imposed work load, the use of more or less efficient work methods, and stress level (26).

---

*HPNS is discussed in Report 12.

Performance degradation may be regarded as a reduction in force and work-producing capabilities, an increased energy cost per unit of work accomplished, or an increase in task completion times. The severity of the degradation depends, to a large degree, on the specific nature of the task. For example, Streimer (45) found that for a given torque there are optimal combinations of crank length and load level for maximal work rates on a rotary task (turning a crank). Energy costs were found to increase from 12-50% over surface equivalents. Thus, the selected work method may be a critical variable in working capacity.

Range and speed of motion can be significantly reduced in underwater work because of inadequate equipment design which results in a restricted work envelope. That the standard Mark V breastplate restricts overhead reaching is well known and provides a graphic example. In research comparing the range of joint motion in the Mark V and Mark XII diving systems, the investigators found mean percentage losses in the range of motion to be significantly greater for the Mark V in 6 of 14 movements in the water. Movement in a more viscous medium also presents a problem, because a fourfold increase in force is required to double the speed of movement or move twice the surface area through the water (8, 9). The implications of inadequate equipment design for safety and effectiveness, while obvious, are often left unconsidered when planning a work methodology. The development of increased strength to handle increased work is also frequently neglected.

Agility is seriously degraded for the same reasons given above. Awkward gross body movements result in reduced mobility around work sites and is further complicated by the lack of appropriate restraint systems to provide counter pressure, and by reluctance to modify work methods for near-neutral buoyancy states.

Minimal levels of strength and endurance are required to perform any given task. Divers at work will usually maintain sufficient strength to meet demands. If, however, the demand is suddenly increased dramatically in either an altered task or an emergency, the worker may not be able to meet the demand. The development of strength requires that the muscles utilized in a given job be periodically overload-stressed in positions similar to those used in the task. Job-related endurance development requires that the cardiovascular system be overload-stressed periodically in patterns similar to those used in the job. If overload training is not applied in some form, strength and endurance levels may fall below the level needed to perform safely.

Strength is further degraded by cold and fatigue and in some instances by equipment design factors. The ability of a diver to apply force against a resistance is reduced by wearing neoprene gloves (51). The ungloved hand, however, will lose strength if the forearm and hand become chilled. A diver with a cold, neoprene-covered hand may not be able to operate a valve at the end of an extended exposure. It appears obvious that the diver must either prevent the heat loss or organize his job so that he will not depend upon high strength levels near the end of cold dives. The dynamic strength required to re-enter the hatch of a PTC after a cold dive may be great enough to create an unsafe condition in an emergency. Aids and techniques to overcome this problem are required.

Equilibrium and balance are sharply degraded in water. Visual and kinesthetic cues are absent or distorted and there is a tendency to veer during underwater swimming (1). Swimming in turbid water frequently results in swimming in circles. Vestibular and kinesthetic receptor mechanisms can become disrupted to such an extent that complete loss of space orientation results (33). It is important to be able to recognize the meaning of the changed cues that are found between air and water and to design restraints which will provide compensatory conditions. HPNS, inert gas narcosis, and cold can also contribute to equilibrium problems.

Interference with coordination can result in impaired ability to handle cables or umbilicals or to align flanges. Errors in such behavior can result in amputation or crushing of fingers and limbs, or in failure to complete the job. Distortion of visual cues, slowed movement due to viscosity or cold stress, effects of inert gas narcosis, and restrictive equipment can all contribute to the problem. Since this behavior is so degraded it is necessary to develop training conditions to prepare the diver so that the procedures he uses will be safe and effective under the constraint. Subtasks should be designed so that only grossly coordinated movements are required to complete them successfully.

Assessment of the effect of impaired physical working capacity in underwater work conditions is not well documented. There is, however, consistency in the findings about the degradation of specific aspects of physical working capacity which result in altered effectiveness. The implications for training and improved equipment and task design are clear. There is a need for biomechanical analysis of work and safety procedures to determine their relative effectiveness. The measurement of energy requirements for specific conditions of work should be established to encourage redesign of those activities which require excessive effort. There is little justification for the risks inherent in the "pigsac" (pull intently, grunt, strain and curse) work method.

Positive changes in diver fitness levels, biomechanical efficiency, and training for specific skill requirements can be achieved if the specific physical work requirements are systematically analyzed for diving as they have been for other industries and activities. The evaluation of current levels of performance against theoretical biomechanical models is not only possible but necessary for the improvement of underwater work practices.

IV. RECOMMENDATIONS

The committee recommends that research is needed on the following topics to provide information on the cognitive and psychomotor aspects of diving. These topics are arranged in order of priority.

1. There is an urgent need for systematic identification of the specific kinds of work requirements that are current or future problems for working divers. Examples of these problems are:

    a. Task analysis of the jobs divers perform, to increase safety and effectiveness. Elements should include:

        1) Energy costs and physical working capacities

        2) Sensory requirements, e.g., hearing, vision, touch

        3) Cognitive requirements, e.g., memory, reasoning, computation

        4) Psychomotor assessment, e.g., dexterity, coordination

2. Human engineering studies of all diver-related life-support systems, work-support systems, and tools should be carried out to ensure compatibility with human capabilities and safety.

3. Stress adaptation studies should be conducted to determine the mechanisms for specific adaptation to stressors which limit:

    a. Sensory and perceptual capabilities, e.g., underwater vision, spatial orientation, and tactile discrimination

    b. Cognitive processes, e.g., procedure-following, memory, vigilance, problem solving

    c. Psychomotor processes, e.g., dexterity, simple and complex assembly, coordination

    d. Physical work capacity, e.g., strength, endurance, range and speed of motion, agility

4. When the limiting mechanisms are known, compensatory programs should be established to deal with these problems. Solutions will result if the following are improved:

    a. Selection criteria and procedures

    b. Training and education

    c. Equipment design

d. Work strategies and procedures

e. Task restructuring

f. Job aids

V. PRINCIPAL U.S. LABORATORIES CURRENTLY INVOLVED IN UNDERWATER PERFORMANCE RESEARCH

University Laboratories

1. Dept. of Kinesiology, Underwater Research Facility, University of California, Los Angeles
Performance testing under shallow water conditions, diving safety research project, underwater work tolerance tables, biomedical analysis, work system evaluation, exercise physiology, equipment evaluation, telemetry

Glen H. Egstrom

2. Dept. of Physiology, University of Hawaii, Honolulu, Hawaii
Performance testing under open-sea and saturation conditions, Aegir mobile habitat, exercise physiology, behavioral effectiveness

E. L. Beckman

3. F. G. Hall Environmental Laboratory, Duke University Medical Center, Durham, North Carolina
Performance testing under saturation conditions, HPNS, inert gas narcosis, exercise physiology

Peter Bennett

4. Institute for Environmental Medicine, University of Pennsylvania, Philadelphia, Pennsylvania
Performance testing under saturation conditions, HPNS, inert gas narcosis, psychophysical performance

C. J. Lambertsen, Dorothy E. Fletcher

5. Marine Science Center, University of Southern California, Avalon, California
Telemetry, open-sea monitoring, exercise physiology

A. J. Pilmanis

Private Laboratories

1. Battelle Columbus Laboratories, Columbus, Ohio
   Diving systems, tool studies

   Arthur Coyle

2. Oceanautics, Landover, Maryland
   Human engineering research on displays and information transfer, performance in cold water

   W. S. Vaughan, Jr.

Government Laboratories

1. Behavioral Science Dept., Naval Medical Research Institute, Bethesda, Maryland
   Neurophysiology, human engineering, operant behavior, training

   A. J. Bachrach

2. Navy Experimental Diving Unit, Panama City, Florida
   Performance testing under saturation and open-sea conditions, equipment evaluation, systems evaluation, ergometry

   W. Spaur

3. Naval Coastal Systems Laboratory, Panama City, Florida
   Ocean simulation facility shared with and staffed by EDU, tool evaluation and development, underwater communications, thermal protection

   Tom Odum

4. Naval Undersea Center, San Diego, California
   Diver-assist work platforms systems

   Howard Talkington

5. Submarine Medical Research Laboratory, Groton, Connecticut
   Shallow saturation and shallow water testing, vision, hearing, habituation effects

   G. Moeller

APPENDIX A - EXAMPLES OF COGNITIVE AND PSYCHOMOTOR PROBLEMS ENCOUNTERED IN OPERATIONAL DIVING

Sensory and Perceptual Processes

Problem	Example	Contributing Factors
Visual discrimination	Determination of task completion	Low light Turbidity Perceptual narrowing
Tactile discrimination	Inability to discriminate shape, size differences, e.g., of knobs	Cold Protective equipment
Sound localization	Location of ship propellers	Altered sound conduction
Color confusion	Inability to use color as a coding device	Low light Turbidity Color adaptation
Spatial orientation	Uncertainty about direction of surface, workplace, habitat safety areas	Vestibular disturbance Lack of visual cues
Temporal orientation	Misjudging bottom time	Fatigue Concentration on task Possible physiological impairment
Distance judgments	Interference with eye/hand coordination	Face mask distortion Turbidity Lack of visual reference objects

Cognitive Processes

Problem	Example	Contributing Factors
Surveillance, vigilance, monitoring	Attention lapses in checking status of gauges	Distraction Apprehension Fatigue Cold Narcosis

Short-term information retrieval		Fatigue Cold
Long-term information retrieval	Reduced information transmission in post-dive report	Cold
Information processing facility	Increased errors in arithmetic computations	Narcosis
Decision making, problem solving	Inappropriate or delayed response to an emergency	Narcosis Hypoxia CO_2
Assigning priorities, selecting strategies	Overlooking of high priority tasks, e.g., life-support system	Narcosis Work load
Evaluating own efficiency, safety, and health	Misjudging own stamina in planning bottom time	Stress Job aids
Articulation	Inability to move jaw freely in speech	Fatigue Equipment design Noise
Transmission	Misinterpretation of working messages by both receiver and sender	Mask design Communications system design Noise Message content
Interpretation	Action is delayed and excess effort is expended due to necessity for repetition	Communications procedures Variations in background

Psychomotor Processes

Problem	Example	Contributing Factors
Dexterity	Difficulty in making fine, discrete motions, e.g., manipulating small controls	Cold Equipment

Arm-hand steadiness	Tremor	HPNS
Simple assembly	Tooker patch application slowed	Cold
Complex assembly	Slow/awkward movements in rigging a difficult lift	Equipment
Multilimb coordination	...	...

Physical Working Capacity

Problem	Example	Contributing Factors
Range/speed of motion	Restricted work envelope, e.g., limited overhead reach	Equipment Strength Viscosity
Agility	Awkward gross body movements and mobility, e.g., changing work locations	Equipment design Fitness Viscosity
Hand gripping/ torqueing strength	Inability to exert adequate force on quick-release mechanism	Cold Glove design
Static strength	Failure to maintain grip on a safety line in a current	Fatigue Excessive work load Cold
Dynamic strength	Strain on re-entering a PTC after long exposure and work load	Fatigue Excessive work load Respiratory work Cold
Equilibrium	Veering tendency during underwater swimming	Neutral buoyancy Changed meaning of cues from air to water Design of restraints Turbidity Fatigue Narcosis HPNS

		Vestibular and kinesthetic malfunction
Coordination	Impaired ability to handle cables	Equipment Viscosity Cold Narcosis
Stamina, cardiovascular endurance	Work capacity insufficient to meet demands of job	Fitness Inappropriate assessment of job energy cost

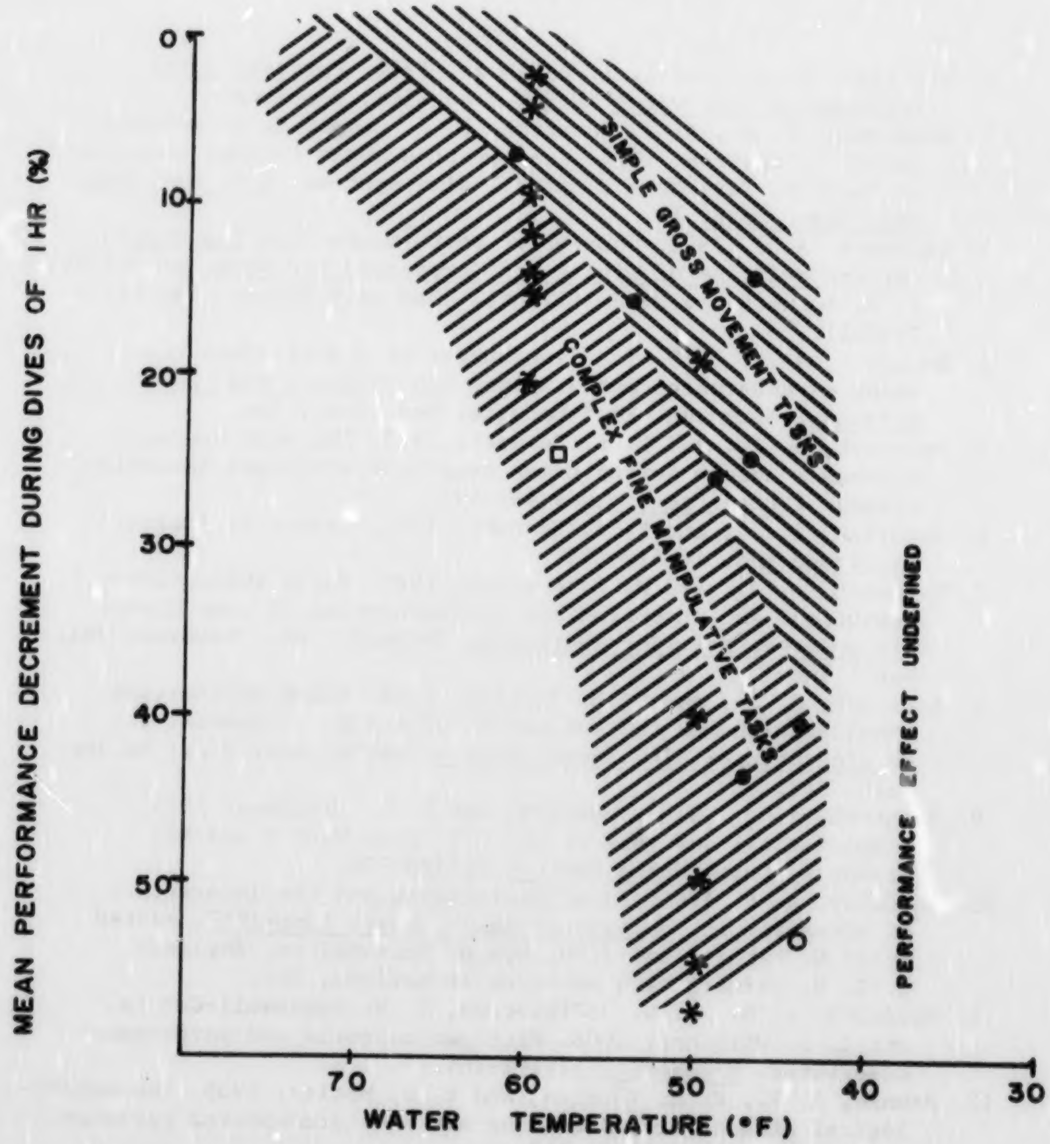


Figure 1.4. The Average Decrement in Psychomotor Performance During Hour Exposures to Cold Water

- ● BOWEN (1968)
- ✱ STANG & WIENER (1970)
- ○ WELTMAN & EGSTROM, ET AL (1971)
- □ WELTMAN & EGSTROM, ET AL (1970)

REFERENCES

1. Adolfson, J. A., and T. E. Berghage. 1974. Perception and Performance Underwater. N.Y.: Jonn Wiley and Sons.
2. Armstrong, F. W., A. J. Bachrach, K. J. Conda, M. J. Holiman, and G. H. Egstrom. 1974. Co-operative human factors analysis of the U.S. Navy Mark V and XII dive systems. U.S. Nav. Med. Res. Inst. Rept. 7.
3. Bachrach, A. J. 1975. Underwater performance. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. H. Elliott. (2nd ed.) London: Bailliere Tindall.
4. Bachrach, A. J. 1975. The development of standardized assessment of underwater performance. 4th Undersea Med. Soc. Workshop. Bethesda, Md.: Undersea Med. Soc., Inc.
5. Bachrach, A. J., and P. B. Bennett. 1973. The high pressure nervous syndrome during human deep saturation and excursion diving. Foersvarsmedicin 9:490-495.
6. Bachrach, A. J., and P. B. Bennett. 1973. Tremor in diving. Aerospace Med. 44:613-623.
7. Bachrach, A. J., and M. E. Bradley. 1975. Early indications of behavioral and physiological dysfunctioning in deep dives. 3rd Undersea Med. Soc. Workshop. Bethesda, Md.: Undersea Med. Soc., Inc.
8. Bachrach, A. J., and G. H. Egstrom. 1974. Human engineering considerations in the evaluation of diving equipment. In: Working Diver--1974. (Symp. Proc.). Washington, D.C.: Marine Tech. Soc.
9. Bachrach, A. J., G. H. Egstrom, and S. M. Blackmun. 1975. Biomechanical analysis of the U.S. Navy Mark V and XII diving systems. Human Factors 17:328-336.
10. Baddeley, A. D. 1966. Diver performance and the interaction of stresses. In: Underwater Assoc. Rept. 1966-1967, edited by J. N. Lythgoe and J. D. Woods. Charshalton, England: T. G. W. Industrial & Research Promotions, Ltd.
11. Baddeley, A. D., J. W. DeFigueredo, J. W. Hawkswell-Curtis, and A. N. Williams. 1968. Nitrogen narcosis and performance underwater. Ergonomics 11:157-164.
12. Behnke, A. R., R. M. Thomson, and E. P. Motley. 1935. The psychological effects from breathing air at 4 atmospheres pressure. Am. J. Physiol. 113:554-558.
13. Bennett, P. B. 1965. Psychometric impairment in men breathing oxygen-helium at increased pressures. U.K. Roy. Nav. Personnel Res. Comm. Rept. NSTIC/08342166.
14. Bennett, P. B. 1974. Systems of underwater performance assessment. In: The Development of Standardized Assessment of Underwater Performance, edited by A. J. Bachrach. Bethesda, Md.: Undersea Med. Soc., Inc.

15. Bennett, P. B. 1975. Inert gas narcosis. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. N. Elliott. (2nd ed.) London: Bailliere Tindall.

16. Biersner, R. J. 1971. Human performance at great depths. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. N. Y.: Academic Press.

17. Biersner, R. J. 1974. Performance effects of fatigue in divers. In: Proc. 1st Annual Meeting N. Pacific Branch Undersea Med. Soc. Avalon, Calif.: Univ. So. Calif.

18. Biersner, R. J., and B. J. Cameron. 1970. Memory impairment during a deep helium dive. Aerospace Med. 41:658-661.

19. Bowen, H. M. 1968. Diver performance and the effects of cold. Human Factors 10:445-464.

20. Bowen, H. M., B. Andersen, and D. Promisel. 1966. Studies of divers' performances during the SeaLab II Project. Human Factors 8:183-199.

21. Bowen, H. M., and R. D. Pepler. 1967. Studies of the performance capabilities of divers: The effects of cold. Tech. Rept. U.S. Office Nav. Res. Darien, Conn.: Dunlap and Associates, Inc.

22. Cattell, R. B. 1971. Abilities: their structure, growth, and action. Boston: Houghton Mifflin Co.

23. Chiles, W. D., E. A. Alluisi, and O. Adams. 1968. Work schedules and performance during confinement. Human Factors 10:143-196.

24. Dickson, J. F., Jr., C. J. Lambertsen, and J. G. Cassils. 1971. Quantitation of performance decrements in narcotized man. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. N.Y.: Academic Press.

25. Egstrom, G. H. 1970. Effect of equipment on diving performance. In: Scripps Inst. of Oceanography. Human Performance and Scuba Diving Proc. Chicago: The Athletic Institute.

26. Egstrom, G. H., and G. Weltman. 1974. Underwater work performance and work tolerance: Final Report. Univ. Cal. Sch. Eng. Suppl. Sci. Rept. UCLA-ENG-7427.

27. Egstrom, G. H., G. Weltman, A. D. Baddeley, W. J. Cuccaro, and M. A. Willis. 1972. Underwater work performance and work tolerance. Univ. Cal. Sch. Eng. Suppl. Sci. Rept. UCLA-ENG-7243.

28. Fitts, P. M., and M. I. Posner. 1967. Human Performance. Belmont, California: Brooks-Cole.

29. Green, J. B. 1861. Diving with and without armour. In: The Aetiology of Compressed Air Intoxication and Inert Gas Narcosis, edited by P. B. Bennett. London: Pergamon.

30. Guilford, J. P., and R. Hoepfner. 1971. The Analysis of Intelligence. N.Y.: McGraw Hill.

31. Hamilton, R. W., Jr. (in press) Psychomotor performance in normoxic neon and helium at 37 atmospheres. In: 5th Symp. Underwater Physiol., edited by C. J. Lambertsen.

32. Hunter, W. L., Jr., and P. B. Bennett. 1974. The causes, mechanisms, and prevention of the high pressure nervous syndrome. Undersea Biomed. Res. 1:1-28.

33. Kennedy, R. S. 1974. General history of vestibular disorders of diving. *Undersea Biomed. Res*. 1:73-82.

34. Kiessling, R. J., and C. H. Maag. 1962. Performance impairment as a function of nitrogen narcosis. *J. Appl. Psychol.* 46:91-95

35. Luria, S. M., S. H. Ferris, C. L. McKay, J. A. S. Kinney, and H. M. Paulson. 1972. Vision through various scuba facemasks. *U.S. Nav. Sub. Med. Res. Lab. Rept. NSMRL 734*.

36. Luria, S. M., and J. A. S. Kinney. 1970. Underwater vision. *Science* 167:1454-146.

37. MacInnis, J. 1971. Performance aspects of an open sea saturation exposure at 615 feet. In: *Proc. 4th Symp. Underwater Physiol*., edited by C. J. Lambertwen. N.Y.: Academic Press.

38. Miller, J. G. 1964. Adjusting to overloads of information. *Res. Nerv. Ment. Diseases* 42:87-100.

39. Mills, A. W. 1956. Finger numbness and skin temperature. *J. Appl. Physiol*. 9:447.

40. Nelson, J. G. 1968. Effect of water immersion and body position upon perception of the gravitational vertical. *Aerospace Med*. 39:806-811.

41. O'Reilly, J. P. 1974. Performance decrements under hyperbaric He-O_2. *Undersea Biomed. Res*. 1:353-361.

42. Ross, H. E., S. R. King, and H. Snowden. 1970. Vertical distance judgements underwater. *Psychol. Forsch*. 33:155.

43. Shilling, C. W., M. Werts, and N. Schandelmeier. (in press) *Underwater Engineering Handbook*. N.Y.: Plenum.

44. Stang, P. R., and E. L. Wiener. 1970. Diver performance in cold water. *Human Factors* 12:391-399.

45. Streimer, I. 1969. A study of work-producing characteristics of underwater operations. Rept. N00014-67-C-0363, SD69-20. Downey, California: North American Rockwell Corp.

46. Vaughan, W. S., Jr., and B. G. Anderson. 1973. Effects of long-duration cold exposure on performance of tasks in naval inshore warfare operations. Landover, Md.: Oceanautics, Inc.

47. Weltman, G. 1970. Diver work methods. In: *Proc. Scripps Inst. Oceanography*. *Human Performance and Scuba Diving*. Chicago: The Athletic Institute.

48. Weltman, G., R. A. Christianson, and G. H. Egstrom. 1965. Visual fields of the SCUBA diver. *Human Factors* 7:423-430.

49. Weltman, G., R. A. Christianson, and G. H. Egstrom. 1970. Effect of environment and experience on underwater work performance. *Human Factors* 12:587-598.

50. Weltman, G., and G. H. Egstrom. 1968. Measuring work effectiveness underwater. *Los Angeles Region Symp. Marine Tech. Soc*.

51. Weltman, G., G. H. Egstrom, M. A. Willis, and W. Cuccaro. 1971. Underwater work measurement techniques: Final Report. *Univ. Calif. Sch. Eng. Appl. Sci. Rept. UCLA-ENG-7052*.

52. Williams, T. 1970. *Optical Properties of the Sea*. Annapolis, Md.: *U.S. Nav. Inst*.

EXCHANGE OF INERT GASES, OXYGEN AND CARBON DIOXIDE

Part #7

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Brian A. Hills, Ph.D. (Chairman)
Chief, Hyperbaric Physiology Section
Marine Biomedical Institute
University of Texas Medical Center
Galveston, Texas

Kenneth N. Ackles, M.D.
Head, Pressure Physiology Group
Defense and Civil Institute of Environmental Medicine
Downsview, Ontario, Canada

H. V. Hempleman, Ph.D.
Superintendent
Royal Naval Physiological Laboratory
Alverstoke, Hants, England

Alan R. Krasberg
Director of Research and Development
K.D. Marine Overseas, Ltd.
Aberdeen, Scotland

TABLE OF CONTENTS and Organization for part 7

Exchange of Inert Gases, Oxygen and Carbon Dioxide

I. INTRODUCTION 1

II. STATE OF THE ART AND NEEDED RESEARCH 1

A. The Perfusion-Diffusion Confusion

B. The Primary Event in Decompression

C. Critical Insult for Decompression Sickness

D. Problems Specific to Each Category of Decompression Sickness

E. Basic Treatment-Related Research

III. PRIORITIES 6

IV. SUITABLE LABORATORIES 6

I. INTRODUCTION

Diving is a hazardous occupation, yet one which is essential for the exploitation of offshore resources. It is vital to ensure the welfare and safety of the diver and, undoubtedly, the foremost problem concerns decompression.

Currently most diving procedures are entirely empirically based; they tend to cope with only a limited range of conditions. For example, a calculation method which can provide apparently safe decompression schedules for exposures down to 400 feet may fail completely when extrapolated to 500 feet. This type of trial and error modification can be very time consuming and expensive, to say nothing of the danger involved to the subjects. Such an unsatisfactory situation has arisen both from a lack of knowledge of the underlying biophysics and from a disregard for established basic principles.

What is really needed is a fundamental understanding of gas exchange and bubble formation. This is not only essential to elucidating the major features of the true model for formulating decompression procedures, but also to our understanding of the kinetics of inert gas narcosis, the High Pressure Nervous Syndrome, and numerous other disorders observed under pressure.

Past endeavours have highlighted certain issues vital to the establishment of a fundamental model for tissue gas exchange and distribution. These vital issues provide a convenient classification for the research which this committee considers necessary.

II. STATE OF THE ART AND RESEARCH NEEDED

A. The Perfusion-Diffusion Confusion

A more precise and quantifiable understanding of the mode of uptake of inert gases is needed. Clearer definitions of the roles played by blood perfusion and diffusion and their interaction in controlling gas transfer in the relevant tissues are needed. This should be approached using both direct and indirect methods.

Direct methods which are in current use include:

1. Mass spectrometry: monitoring whole body washout of dissolved inert gases and, more particularly, techniques which investigate inert gas exchange in individual tissues. Much effort needs to be expended in the interpretation of the results obtained by this method.

2. Tracer techniques: these are particularly appropriate for monitoring the simultaneous uptake of multiple inert gases in individual tissues. The utilization of multiple tracers has many advantages in differentiating between the various models.

3. Autoradiography: this technique has not yet been used in connection with diving research.

4. Bubble detection: various methods which estimate gas uptake from the extent of decompression needed to precipitate the gaseous phase or from the response of the monitoring technique to a fixed decompression. Such techniques already include ultrasound and conductivity.

5. Any other method which proves viable: further techniques are urgently needed for estimating the gas content of a tissue.

Indirect methods which have been used generally involve provoking marginal symptoms of decompression sickness. These have the great advantage of focusing attention on the relevant tissue(s) without having to identify them anatomically. Such methods are limited by the assumption that marginal symptoms are always provoked by the same critical insult. Much can also be learned about the limitations of inert gas transfer from switching inert gases and following the transient changes in the imminence of decompression sickness.

Clearly, the same approaches can also be utilized for studying the kinetics of gas transfer in the tissues relevant to inert gas narcosis, HPNS, isobaric vestibular dysfunction, hyperbaric urticaria, and possibly, oxygen toxicity.

Much investigation of the influence of various environmental parameters upon gas transfer is needed. These should include:

1. Decompression: differences between gas uptake and elimination have been used as a convenient means of detecting the separation of gas from solution in tissue. Whatever the true explanation, any asymmetry between uptake and elimination is very important in calculating decompression schedules.

2. Oxygen: investigation of the effect of the oxygen partial pressure upon inert gas transfer mediated by hemodynamic changes or any other mechanism. It is recommended that particular attention be focused on the effect of the oxygen level upon the driving force for inert gas elimination during decompression. Further elucidation of the inherent unsaturation/oxygen window of tissue is needed, not only because of its influence upon the kinetics of transfer but for determining the onset of bubble formation.

3. Carbon dioxide and water vapor: similar considerations apply to these gases as outlined for oxygen.

4. Temperature: this will affect gas solubility and diffusion coefficients, blood perfusion, vascularity, and probably other relevant factors.

5. Pressure per se: little is known of the effects of this parameter, particularly at the greater depths.

6. Exercise: this is a controversial area, particularly when undertaken during decompression; it needs more attention.

7. Other stresses: there are many, such as emotional considerations, whose possible influence remain unquantifiable, even if identified.

B. The Primary Event in Decompression

Most authorities now agree that the primary event leading to decompression sickness is the establishment of a stable gaseous phase, either by nucleation *de novo*, or by the activation of pre-existing nuclei. Areas for investigation of the formation and activation of nuclei include:

1. Mechanisms of nucleus formation: this should include studies of two-phase systems and interfaces which could be relevant to biological situations. It has been proposed that the energy for activating a nucleus can be provided by nuclear disintegration, cosmic radiation, tribonucleation, ultrasound, and Reynold's cavitation.

2. Characterization of the "reservoir" of nuclei: it should be established whether there are pre-existing nuclei and, if so, their distribution should be determined. Present techniques involve studies of solution "memory" to high hydrostatic pressure, but much more work is needed in this area.

3. Stabilization of nuclei: the effects of mechanical properties of the medium, such as liquid and gel.

4. Distribution of nuclei: it is desirable to know the spatial distribution of nuclei within tissue since this must influence the mode of growth of the gaseous phase.

5. Bubble growth: it is useful to know the dependence of the growth of activated nuclei upon the various physical parameters, particularly bubbles of mixed composition. These should include the effects of the dynamics of the fluid, in the case of intravascular bubbles, and such factors as the chemical affinity of the medium for one or more of the component gases. Ideally, the findings should be incorporated into a mathematical model for general application.

6. Bubble-bubble interaction: these studies should include coalescence and interdiffusion in a variety of appropriate situations.

C. Critical Insult for Decompression Sickness

The primary event can be manifested as symptoms in a number of ways. The mechanisms which have already been postulated include:

1. The mere existence of the gas phase as the hidden assumption in many of the more popular calculation methods used to derive decompression schedules.

2. A critical bubble volume which can block a blood vessel or bend a nerve ending beyond its pain-provoking threshold.

3. Blood-bubble interaction which can cause various forms of hematological disorder, and various autoimmune responses.

4. Bubble-tissue interactions leading to extravascular biochemical abnormalities.

The critical insult may not be the same for each of the major manifestations of inadequate decompression. It is not certain that the prevention of limb bends will necessarily prevent other symptoms. The major categories of acute decompression sickness are: 1) Limb bends and cutaneous manifestations; 2) Audio-vestibular disorders; 3) Spinal cord involvement; 4) Symptoms involving higher centers of the brain; 5) Chokes.

The more specific questions which must be answered concern the anatomical identity of the critical tissue(s) responsible for each category, whether or not a bubble is directly involved, and whether it is located intravascularly or extravascularly. The identification of the tissue is necessary: 1) to ensure rational therapeutic procedures; 2) to define the mathematical model more precisely; 3) to ensure more relevant monitoring methods; and 4) to get a better assessment of interactions.

D. Problems Specific to Each Category of Decompression Sickness

1. Limb bends: although this form of acute decompression sickness has been known for over a century, the mechanism for provoking pain has not been established. Various hypotheses include the distortion of nerve endings by gas or fluid or both, ischemic pain due to vascular occlusion by various forms of circulating emboli (gas, fat, or thrombi); there is also the possibility that the pain is biochemical in origin. Whether the pain is referred rather than direct is also still a question. Another factor to be accommodated by the theory is the known effect of acclimatization (adaptation) with consecutive exposure to pressure.

2. Itching and rashes: these forms of skin bends appear to be an air phenomenon associated with direct contact of the skin with a gaseous environment, but are of no great practical importance.

Skin mottling, on the other hand, has more serious implications and its etiology remains essentially unknown.

3. Audio-vestibular disorders: fundamental studies of the effects of cavitation and possible fluid shifts upon the cochlear-vestibular end organs are needed.

4. Spinal cord involvement: it is of considerable importance to ascertain whether embolization is intravascular or extravascular and the reason why some areas are much more susceptible than others.

5. Higher centers of the brain: it is generally believed that decompression sickness in these areas is due to vascular occlusion by gas emboli. Attention needs to be paid to the origin of probable arterial gas emboli.

6. Chokes: it is generally agreed that this phenomenon is sufficiently understood and is in any case a rare event not warranting further investigation.

7. Bone: dysbaric osteonecrosis cannot unequivocally be considered a manifestation of inadequate decompression, although it probably is. Many fundamental studies of basic physiological responses of bone to the various phases of hyperbaric exposure are needed.

E. Basic Research-Related Treatment

Greater knowledge of inert gas transfer would aid the rational prescription of therapeutic procedures in the following areas:

1. The use of pharmacological agents to modify gas transfer.

2. Further fundamental studies of the behavior of bubbles *in vivo*, including the effects of compression and/or oxygen breathing.

3. Other techniques for emergency medical management where recompression is not available. These should include administering low-molecular weight dextran, heparin, and so forth.

F. Other Important Phenomena

1. Hyperbaric arthralgia: this requires further investigation since it can on occasion seriously impair the diver's performance and could have chronic implications.

2. Isobaric disturbances: hyperbaric urticaria and vestibular disorders induced simply by gas switching at fixed pressure warrant much attention, since they could provide insight into the mechanism for causing the same overt signs by change of pressure.

3. Counterdiffusion supersaturation and gas-induced osmosis: both are interesting phenomena which have been demonstrated in vitro under steady-state conditions. They have been offered as explanations for the preceding phenomenon (isobaric disturbances) and their further implications warrant additional investigation.

III. PRIORITIES

The following areas are considered of paramount importance in the theoretical understanding and practical development of diving procedures:

1. Degree of supersaturation of tissue by gas, if any, for bubble growth.

2. The relative contributions of diffusion and blood perfusion in controlling tissue gas exchange.

3. Elucidation of the critical insult and degree of insult needed to provoke symptoms of decompression sickness.

4. The site of insult leading to each form of decompression sickness, including the number of tissues, their anatomical identity, and whether the insult occurs intravascularly or extravascularly.

IV. SUITABLE LABORATORIES

Much good fundamental research upon gas exchange and bubble formation can be undertaken in almost any laboratory staffed by personnel familiar with the field. Certain aspects of the work do require hyperbaric facilities. The following laboratories are capable of doing the research necessary to answer the problems associated with inert gases, oxygen, and carbon dioxide:

A. Major laboratories with a substantial history and strong current interest in hyperbaric research:

1. F. G. Hall Environmental Laboratory, Duke University Medical Center, Durham, North Carolina
1000 fsw, saturation, 6 divers, wet, altitude, 6 interlocking chambers, 4500 fsw animal (dog); full laboratory capability
Gas transport, 0_2 tolerance, monitoring, decompression and compression procedures, table testing, treatment.

Peter B. Bennett

2. Institute for Environmental Medicine, University of Pennsylvania, Philadelphia, Pennsylvania
1800 fsw, saturation, 4 divers, wet, altitude, 4 interlocking chambers; 4500 fsw animal (monkey); USN certified; full laboratory capability; International Decompression Data Bank.

Inert gas exchange, counter-diffusion, bubble formation, O_2 tolerance, computer modeling, decompression and compression procedures.

C. J. Lambertsen

3. Marine Biomedical Institute, University of Texas Medical Branch, Galveston, Texas
   800 fsw, saturation, wet, 4 divers
   Gas transfer and decompression theory, decompression meter development, bone necrosis, full laboratory capability.

   Brian A. Hills

4. S.U.N.Y. at Buffalo, New York
   5000 fsw, wet, 3 divers, altitude
   Gas transport, gas exchange

   Herman Rahn

5. Tarrytown Labs, Ltd., Tarrytown, New York
   1000 fsw, dry only, saturation to 675 fsw, 2 divers, altitude, small animals to 5000 fsw, altitude
   Table development, use of neon, nitrogen saturation-excursion, computer control and monitoring, strong commercial orientation.

   R. W. Hamilton, Jr.

6. Taylor Diving and Salvage Co., Belle Chasse, Louisiana
   2000 fsw, wet, saturation, 6 divers
   Support staff, capable of expansion

   Peter Erickson

7. Texas A&M University, College Station, Texas
   600 fsw, large animals
   Table development, hydrogen

   William P. Fife

8. Virginia Mason Research Center, Seattle, Washington
   1500 fsw, saturation, 2 divers; 400 fsw, animal (large); 1800 fsw, animal (small); full laboratory capability.
   Table development, inert gas exchange and transport, decompression pathophysiology and bone necrosis, Doeppler monitoring

   Kent H. Smith

B. Laboratories with current work or interest in gas exchange

1. Beth Israel Medical Center, New York, New York
Shallow, small animal, chamber, altitude
Drug and hormone effects on decompression, bone necrosis

Chryssanthos P. Chryssanthou

2. Bowman-Gray Medical School, Wake Forest University, Winston-Salem, North Carolina
Small animal
Auditory-vestibular decompression sickness

James G. McCormick

3. Colorado State University, Fort Collins, Colorado
250 fsw, 10 divers, large animals, altitude
Altitude decompression

Peter Hall

4. Institute for Applied Physiology and Medicine, Seattle, Washington
300 fsw, 2 divers
Doeppler monitoring, gas transport

Merrill C. Spencer

5. St. Lukes Hospital, Milwaukee, Wisconsin
225 fsw, 8 divers
Treatment of decompression sickness, caisson work, inert gas transport

Eric P. Kindwall

6. University of Hawaii, Honolulu, Hawaii
Aeger mobile habitat, 600 fsw, DDC on shore
Sea trials, bubble formation

David Yount

7. University of Rochester, Rochester, New York
Animal chamber
Pharmacological treatment of decompression sickness

A. T. K. Cockett

C. Laboratories limited in facilities or orientation toward decompression, or those which are inactive at this time.

1. Harbor Branch Foundation, Fort Pierce, Florida
   2 lockout submersibles, 1500 fsw; 1000 fsw DDC, saturation, on R. V. Johnson
   Open-sea testing

2. Sea-Space Research, Harvey, Louisiana
   Chamber to be operational June 1976
   Commercial table computation, use of hydrogen

   Peter Edel

3. Scripps Institute of Oceanography, La Jolla, California
   No laboratory chamber
   Fundamental decompression theory

   Hugh Bradner

4. University of North Dakota, Grand Forks, North Dakota
   Extensive animal chamber complex
   Oxygen toxicity, chronic inert gas effects

   Thomas Akers

5. University of Southern California at Avalon, California
   225 fsw, 4 divers
   Treatment, telemetry, open-sea monitoring

   Andrew J. Pilmanis

6. Westinghouse Ocean Research and Engineering Center, Annapolis, Maryland
   1500 fsw, wet, saturation, 3 divers

   W. J. O'Neill

7. Wrightsville Marine Biomedical Laboratories, Wilmington, North Carolina
   600 fsw, animal (large); 3200 fsw, animal (gill breathers)
   Compression effects, HPNS

   Ralph W. Brauer

D. Military laboratories or facilities.

1. Naval Coastal Systems Laboratory/Naval Experimental Diving Unit, Panama City, Florida
   2500 fsw, saturation, wet, large staff; full laboratory capability
   Decompression table development (equipment and task oriented)

   W. H. Spaur

2. Naval Medical Research Institute, Bethesda, Maryland
   3300 fsw, saturation to 2200, wet 2200 (due 1978), altitude; full laboratory capability
   Basic research in support of diving operations

   Large staff

3. Naval Submarine Medical Research Laboratory, Groton, Connecticut
   300 fsw, 3 divers, dry; full laboratory capability
   Nitrogen saturation and saturation, excursion diving to 300 fsw

   Claude Harvey

4. USAF School of Aerospace Medicine, Brooks Air Force Base, San Antonio, Texas
   200 fsw, 4 divers, 2 chambers, altitude
   Treatment of decompression sickness, training of physicians

   Jefferson C. Davis

5. U.S. Navy Submarine Development Group One, San Diego, California
   Mark I Deep Diving System (1000 fsw DDC) on MV ELK RIVER
   Sea trials

   Paul Linaweaver

USE OF INERT GASES OTHER THAN NITROGEN AND HELIUM

(Retitled - Assessment of Gases Suitable for Diving)

Part #8 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Robert W. Hamilton, Ph.D. (Chairman)
Tarrytown Labs, Ltd.
Tarrytown, New York

Ralph W. Brauer, Ph.D.
Institute of Marine Biomedical Research
Wilmington, North Carolina

Mr. Peter O. Edel
Sea-Space Research
Harvey, Louisiana

Mr. Robert Gilardi
AIRCO Industrial Gases
Murray Hill, New Jersey

TABLE OF CONTENTS and Organization for part #8

Use of Inert Gases Other Than Nitrogen and Helium
(Retitled - Assessment of Gases Suitable for Diving)

I. INTRODUCTION.. 1

II. CURRENT RESOURCES... 1

- A. Nitrogen
- B. Helium
- C. Hydrogen
- D. Neon

III. CURRENT PRACTICE.. 4

- A. Mode of Operation
- B. Distribution and Economics of Inert Gases
- C. Current Helium Conservation Practices

IV. PHYSIOLOGICAL PROBLEMS WITH NITROGEN AND HELIUM........... 7

- A. Nitrogen
- B. Helium
- C. Summary of Gas Properties

V. ALTERNATIVES TO CURRENT PRACTICE..........................11

- A. Nitrogen Saturation
- B. Living with Helium
- C. The Case for Neon
- D. Hydrogen
- E. Multi-Gas Mixtures and Gas Sequencing
- F. Other Gases

VI. REQUIREMENTS AND PRIORITIES....................................14

A. Conservation of Helium as a Resource

B. Biomedical Research

C. Operational Aspects of Gases Other Than Helium

D. Priority Categories

VII. FACILITIES...17

I. INTRODUCTION

While underwater a diver must breathe air or other gases at the pressure of the water surrounding him. Oxygen must be in all breathing mixtures, but it becomes toxic when the partial pressure in the mixture exceeds certain limits and must therefore be diluted with an inert gas. Nitrogen is an appropriate diluent for shallow diving, and helium has proved adequate for deeper dives, but there are alternatives to these two gases. This report is concerned with the use and development of alternative inert gases for diving, and also with the assessment of all the diving gases.

Other factors which influence the use of other gases in diving are total world availability of the gases, and their physiological effects and operational advantages or disadvantages.

A number of gases are considered as partial or complete replacements for helium and nitrogen diluents of oxygen. Table 8-1 shows each of the diving gases and several factors which may influence their use.

Neon and hydrogen are the most likely alternatives to helium and nitrogen.* This report deals primarily with the use and availability of helium, nitrogen, neon, and hydrogen; the more exotic alternatives are only briefly considered.

II. CURRENT RESOURCES

The present and future availability of nitrogen, helium, hydrogen, and neon will influence their use as diving gases. Table 8-1 summarizes the status of these resources.

A. Nitrogen

Nitrogen is used in two ways in diving, both as a component of atmospheric air and as nitrogen gas itself. Nitrogen is universally available in unlimited quantities.

B. Helium

Helium is a natural resource which must be mined; it cannot be synthesized. Atmospheric air contains 5 part per million of helium, but extracting helium from this source is impractical. Helium is normally found in association with natural gas. Most of the world's helium comes from natural gas wells in Texas, Oklahoma, and Kansas,

---

*This report is concerned with inert gases; we may and generally do refer to the breathing of helium or neon, for example, with no reference to oxygen. Whether mentioned or not, oxygen must always be present in breathing gas.

Table 8-1. Diving Gas Resources

	Helium	Nitrogen	Neon	Hydrogen
Source	Natural resource associated with certain natural gases	Atmospheric air	Atmospheric air	Chemical reactions
Domestic Commercial Availability	550 million cubic feet/year liquid; U.S. Government produces 300 billion cubic feet/year of gas; 3.3 billion cubic feet/year wasted; 40 billion cubic feet/year of crude in storage	Air separation plants in and near all major cities	Some air separation plants equipped to recover crude neon which can be used for diving	Two liquid plants, about 17 billion cubic feet/year; various gas sources, about 3 1/2 billion cubic feet/year
Limitations on Availability	Depletable natural resource Demand will exceed U.S. supply by mid-1980s	None	Total potentially available neon from air separation plants will not supply diving needs	None
Cost	Moderately high	Low	Very high	Moderately low

which produce about 550 million cubic feet per year for domestic commercial use. An additional 180 million cubic feet per year are produced by the U.S. Government for government use.

A total of about 3.3 billion cubic feet of helium is vented into the atmosphere every year, either in combination with natural gas or separately. Helium returned to the atmosphere in this way is eventually lost from earth. At present, the U.S. produces most of the world's helium; natural gas wells in the Middle East contain some helium, but there are no facilities to recover it. A plant to utilize newly discovered helium is being built in Poland, and there is a small plant in Canada.

Whether the recovery of helium from natural gas is economically feasible depends on the percentage of helium in the source gas. The richest helium source so far is 8%, but 0.1% is more typical. Other factors which affect the practicality of helium recovery are the amount of nitrogen in the natural gas, and the distance to market.

Helium is used in welding, electronics equipment manufacturing, the chemical industry, for leak detection, and in diving. Diving presently consumes 10-15% of total U.S. helium production. Liquid helium is also used for cooling superconducting power transmission cables. Most helium used for this purpose can be recycled and will therefore not be lost to the atmosphere. Estimates of the amount of helium which will be required when its use as a coolant is fully developed run as high as one billion cubic feet a year.

The world is running out of helium. The best estimates suggest that demand will exceed supply by the mid-1980s. The gas fields in the southwest United States will be depleted by that time; only the implementation of conservation practices will extend the supply for an additional ten years. It is unlikely that large new sources of helium will be found. It is not sought as a primary resource, and can only be recovered economically under certain conditions. A distressing thing about this situation is that by the time the less lucrative sources become economically attractive, they will be gone.

C. Hydrogen

Hydrogen is abundant; there is no limit to its availability. Hydrogen can be electrolytically separated from water, but more efficient chemical methods are used in commercial production. The cost of commercial hydrogen is 15-20% that of helium. Cryogenic technology developed for the aerospace program permits hydrogen to be obtained, handled, and stored safely as a liquid.

D. Neon

Neon is present in the atmosphere at about 18 parts per million. Neon is a by-product of the process used to produce nitrogen in air separation plants. Very small amounts of gaseous neon are used commercially for signs and in electronic component manufacture, and liquid neon is used in atomic research and cryogenic cooling.

Because of the relatively small market for neon, it is not usually recovered. Equipment to recover neon adds about $100,000 to the cost of building an air separation plant; the cost is much greater if such equipment is added later. Air reduction plants may produce 200-2500 tons per day of primary product; a typical plant could yield 40,000 cubic feet of crude neon per month. Crude neon, first-run neon, or Neon 75 are names applied to the uncondensed fraction which is removed from the liquid separation column; it is a mixture of about 75% neon and 25% helium. This is the mixture which is being considered for use as a diving gas. Plenty of neon is available for immediate diving needs, but there will probably never be enough Neon 75 to replace helium as a diving gas entirely.

III. CURRENT PRACTICE

There have been many improvements in diving technology in the past three decades, but few of these advances have been adopted in commercial diving, with the notable exception of the saturation mode of diving, and a few innovations designed to meet specialized requirements. Compressed mixed-gas diving is carried out with the minimal level of sophistication necessary to achieve the work tasks imposed; no effort is made to conserve helium, obtain data, or provide more than the minimal level of comfort.

A. Mode of Operation

1. Compressed Air

Whenever depth, exposure time, and job requirements permit, compressed air is selected as the breathing medium. Currently, air diving is used routinely to depths of 150-190 fsw, with occasional dives to 250 fsw under special circumstances. Other breathing mixtures are only considered when air is unacceptable for physiological or other reasons.

2. Helium-Oxygen Mixtures

Helium is the only gas except nitrogen used in commercial diving beyond the safe depths for air diving. Helium may be used alone or in combination with nitrogen as a diluent for oxygen in dives in the depth range from 150 to 1000 fsw and beyond.

3. Surface-supplied Mode

In the range from about 150 to 300 fsw, the simplest form of mixed-gas diving is used. The diver, equipped with demand or semi-closed diving gear, is tethered to a surface base which supplies his breathing mixtures. When the diver has finished his job, he is decompressed in stages, and is finally brought to the surface, where decompression is completed in a surface chamber.

4. Bell System Operations

In the depth range from 200 to 600 fsw, depending to some extent on job requirements at depths shallower than 300 fsw, a diving bell is used to transport the diver to and from his work site. The diver is usually tethered to the bell, which supplies his breathing mixture and provides a safe underwater base. Following completion of the assigned task, the bell is brought to the surface and the diver transfers to a deck decompression chamber while still under pressure.

5. Saturation Diving

In very deep diving operations, the diver is compressed to an appropriate depth in a deck decompression chamber, where he may be under pressure for a period of days or weeks. He is transported in a diving bell to and from his work site while under pressure. At the completion of the multi-day exposure, decompression is accomplished by gradually reducing the pressure in the chamber over a period of several days.

B. Distribution and Economics of Inert Gases

Helium is usually shipped from U.S. sources in liquid form. Containers which store as much as one million standard cubic feet of gas for 30 days with little loss are available. Because helium can now be shipped as a liquid, the price in the North Sea has been reduced by 2/3 in the last five years. Liquid helium is transferred to containers of gas at a pressure of 2000 - 3000 pounds per square inch before delivery to the diving contractors. Other gases are obtained locally.

Compressing and filtering systems produce air at the diving site for offshore use. Nitrogen, or mixtures of nitrogen and oxygen, are supplied and used offshore in cylinders or "quads". Substantial amounts of nitrogen are added to some prepared helium-oxygen breathing mixtures, perhaps as air. Helium is supplied to the diving contractor in two forms, either as pre-mixed gas in cylinders, quads, or trailers, or as pure gaseous helium in quads or trailers, which is then mixed by the diving company. Storing gas creates serious weight, space, and handling problems on most vessels used in diving.

One of the factors in commercial diving which mitigates against the conservation of gas, especially helium, is the practice of passing on to the customer all costs for gas, plus a markup of 10-20%. This practice is customary in all diving operations, except when closed-circuit or reclamation equipment is used, in which case the rental fee for reclamation equipment replaces the markup. These practices offer no incentive whatsoever toward conservation.

C. Current Helium Conservation Practices

In surface-supplied diving the breathing mixtures used by the diver are expelled directly into the water. Additional gas losses occur when diving bells are used, because the gas required to pressurize the bell is vented into the atmosphere when the operation is completed. In saturation diving, even greater gas loss occurs, because the gas used in the deck decompression chamber is also vented after use. The volume of gas lost in this manner may be considerable, particularly if the chamber is large, the operation deep, or decompression times long. Residual cylinder bank losses must be added to those listed above. Diving gas must be delivered to the diver at a pressure corresponding to the pressure at the depth at which it will be used, with sufficient overpressure to supply driving force. When cylinder pressure drops below the appropriate level, the cylinder can no longer be used. Such cylinders are returned to the supplier as much as 25-35% full, depending on the depth of the operation.

Rental for helium conservation equipment is included in the contract bid, and a company employing helium conservation equipment will therefore have a higher bid, all other factors being equal, than a company which doesn't use helium conservation methods. Cryogenic reclaiming systems have been in use for several years in government and commercial hyperbaric facilities, and are commercially available. These systems dump the exhaust gas into a surge tank, and then pump it into cylinders for intermediate storage, or to a cryogenic reclaiming system which removes impurities and stores the reclaimed gas under pressure. Helium reclamation may be used with chamber and bell systems, and also in push-pull diving gear, where the gas is recirculated to the diver through a surface loop. Although such systems cannot be used with most commercial diving gear, closed-circuit equipment, now being introduced into commercial use, offers multi-hour capability at any depth with very little helium consumption. An exposure at 250 fsw using reclamation equipment requires only about 20 standard cubic feet of helium per hour, compared to 6000 standard cubic feet per hour without such equipment.

Adoption of the use of closed-circuit equipment has been delayed because this equipment does not yet have a proven safety record. Though some helium conservation is practiced and some conservation equipment is available, there is no widespread or sustained effort to conserve helium in the diving industry.

IV. PHYSIOLOGICAL PROBLEMS WITH NITROGEN AND HELIUM

A. Nitrogen

Nitrogen is the inert gas of choice for all dives to depths of less than about 150-200 fsw, and it can be used safely at somewhat greater depths under certain circumstances. But even at 150 fsw most divers feel the effects of nitrogen narcosis, which can cause enough deterioration in memory and mental capability to be an operational problem, and impair judgment enough to be a serious safety factor. Nitrogen can therefore not be used in diving beyond the 150-200 fsw range. Although narcosis is reason enough to avoid the use of nitrogen, it has two other properties which make it an unattractive diving gas: it is highly soluble in body fluids, and can therefore be quite difficult to remove safely during decompression, and its density makes it difficult to breathe at increased pressures.

Narcosis and the difficulty of removing nitrogen during decompression can be partially circumvented by using saturation procedures. Breathing resistance results primarily from limitations in the equipment used in the range of nitrogen or air diving.

B. Helium

Helium is light, easy to breathe, has a low solubility and is not narcotic; it is the gas of choice for diving deeper than can be safely done on air. There are, however, physiological problems for the diver breathing helium, problems which are seriously amplified as diving depths approach those of the outer continental shelves. Among these are problems in communication, heat loss, and HPNS.

1. Voice Communication

The destructive effect that breathing helium has on the human voice is well known, though not well understood. Changes in the speed of sound in the gas medium are thought to be responsible for this effect of helium; the degree of distortion is correlated with depth. Helium speech is distorted but still intelligible to the listener and the speaker at sea level, and it remains reasonably intelligible at 200 fsw. In the range between 400 and 600 fsw, helium speech can no longer be understood by an untrained listener unless it is first processed by an "unscrambler". These devices are complex and costly, but they work.

2. Heat Loss

Cold is another problem of deep diving that is particularly exacerbated by the use of helium. Even in equatorial waters, ocean temperatures at helium diving depths are cold enough to limit diving times.

Standard air diving gear or the simple neoprene wet suit of the SCUBA diver is adequate for shallow dives for durations of up to perhaps an hour, provided the depth is not too great. When the depth is greater than about 200 fsw, however, the situation changes because insulation, which depends on dead air space for effectiveness, is compressed and becomes ineffective.

The thermal conductivity of helium is roughly six times greater than that of nitrogen. Consequently, the rate of heat loss in a helium-based gas environment is considerably greater than in air. Cold limits diving performance in many ways: a chilled diver takes much longer to do a given job, is less likely to respond properly to emergencies, and is probably more difficult to decompress.

It has been demonstrated that a diver breathing a helium-oxygen mixture at about 600 fsw can lose all the heat his body can produce into his breathing gas alone. Hot water suits and heaters which warm the breathing gas ameliorate the heat loss problem, but even if the diver is kept warm long enough to finish his work, a bone-chilling sojourn awaits him when he returns to the helium-oxygen filled diving bell. Divers consider the stay in the bell even more stressful and unpleasant than working in cold water.

3. HPNS

Rapid compression, such as might be used to minimize bottom time and hence decompression from very deep dives, causes both human laboratory subjects and experimental animals to exhibit hyperexcitability of the nervous system, a condition known as "helium tremors" or the High Pressure Nervous Syndrome.* Current research indicates that HPNS is not caused by helium itself, but by the rapid rate of compression. In any case, HPNS represents a significant problem for diving, and it may restrict deep diving somewhat. Studies of hyperbaric effects at depths between 1500-2000 fsw, the range which commercial diving expects to use within 5 years, show that even very slow compression rates may cause HPNS. Measures to reduce the effects of HPNS, including the use of drugs or the addition of narcotic gases such as nitrogen or nitrous oxide to the breathing mixture, or substitution of hydrogen for helium, are being investigated.

C. Summary of Gas Properties

Table 8-2 shows the many properties of gases which affect their use in diving. Each gas is related to each of the gas properties; a high positive score indicates a favorable relation between a particular gas and a particular characteristic. No attempt has been made to rank or compare the importance of the different factors.

Table 8-3 summarizes the relevant physical properties of the four inert diving gases.

---

*For a more detailed discussion of HPNS, see Report 12.

Table 8-2. Various gas properties related to gases used in diving; a positive score indicates a favorable relation between that gas and a particular characteristic

Gas Properties	Gas				
	Air	Nitrogen	Helium	Neon	Hydrogen
Cost	+++	++	0	--	+
Narcosis	--	--	+	+	0
Decompression	0	-	+++	++	+
NPNS	0	++	-	-	+
Logistics	+++	++	+	++	-
Heat Loss	+	+	--	0	--
Voice	+	+	-	0	-
Availability	++	++	--	0	++
Handling Safety	0	++	+	+	--
Breathing Resistance	-	-	+	0	++
Contaminants	-	0	++	++	+

The factors in this matrix have been weighted so that one gas in each category is "neutral" and others are arrayed accordingly. A number of additional gases may be considered for use in diving. These include argon, methane, and other hydrocarbons, CF_4 and other freons, nitrous oxide, and sulfur hexafluoride. These gases are important primarily as research tools.

Table 8-3. Physical Properties of Inert Diving Gases

Property and Units	Helium	Neon	Nitrogen	Hydrogen
Molecular weight	4.003	20.183	28.016	2.016
Density, gm/liter, 0°C	0.1785	0.8999	1.2506	0.11124
Viscosity, μ poise, 30°C	200.78	320.78	178.1 (27.4°C)	89.37
Thermal conductivity, (cal/cm·sec·°C) 10^5, 30°C	36.25	11.82	5.95 (15.5°C)	39.7
$\gamma \left[{}^{cp}/_{cv}\right]$, 0-20°C	1.63	1.642	1.404	1.410
Velocity of sound, m/sec, 1 atm 0°C	970	435	337	1284
Solubility, water (Bunsen coeff., 37°C)	0.0087	0.0097	0.0125	0.016
Solubility, olive oil (Bunsen coeff., 37°C)	0.0148	0.0193	0.0609	0.050
Diffusion coeff., 37°C (cm^2/sec) 10^6				
Water	63.2	34.8	30.1	50.7
Oil	18.6	8.34	7.04	-
Vol gas/vol liquid	700	1445	696	848
Boiling point of liquid, °C	-268.9	-246.1	-195.8	-252.5

V. ALTERNATIVES TO CURRENT PRACTICE

The scarcity of helium resources and the physiological and operational limitations of all the gases make it imperative that alternative applications be considered. Some of these are discussed here.

A. Nitrogen Saturation

Procedures for excursion diving from shallow habitats which use nitrogen-oxygen atmospheres have recently been developed for scientific use in undersea habitats. This research has been promoted primarily by NOAA (National Oceanic and Atmospheric Administration), and is often called the NOAA OPS concept. Two findings make the use of these procedures attractive. First, excursions which allow fairly long working times can be made from shallow (50-100 fsw) saturation depths. Second, divers saturated with the nitrogen-oxygen atmosphere are quite resistant to nitrogen narcosis from a deeper excursion. Although these principles appear to be established, more research is needed before they can be adopted in operational diving. Preliminary results suggest that workers should be able to breathe air without appreciable narcosis in the 250-275 fsw range, using a habitat at a depth of 100 fsw. This depth may be extended to the point where oxygen toxicity becomes limiting, if the habitat is deeper to begin with. Since a great deal of helium is used in the 150-250 fsw range, research which will enable these procedures to be used commercially is an important need.

B. Living with Helium

The major physiological defects of helium, voice distortion, heat loss, and HPNS, can be reduced or overcome by proper equipment design and techniques. Helium speech unscramblers make communication relatively easy, and heating the breathing gas, diver, and bell makes cold a manageable problem. The use of trimix, (helium, oxygen, and nitrogen) and a slower rate of compression reduce the effects of HPNS. Measures to make helium reclamation more attractive, such as improved equipment design, training in reclamation techniques, and changes in contracting procedures, need to be implemented to ensure that helium is available in the future for use as a diving gas.

C. The Case for Neon

Neon, like helium, is a chemically inert "noble" gas. It has an atomic weight of 20, compared to 4 for helium and 28 for nitrogen; densities are similarly related. Because of its physical properties, primarily greater density, neon causes far less voice distortion and heat loss than helium, and there is good reason to believe that it will permit more rapid decompression from a deep working dive than is possible with helium. Neon is more difficult to breathe than helium, but despite its density, a diver breathing crude neon at pressures as great as 1200 fsw can still perform moderate work. Neon also does not cause narcosis or a decrease in mental or psychomotor performance. Subjective impressions suggest that there is less tremor with neon than with helium.

Another physical property of neon which might make it the gas of choice under certain conditions is the high heat of vaporization of the liquid phase. Neon is the easiest gas to store and handle as a liquid, and has the highest liquid-to-gas ratio. In circumstances where logistics pose a greater problem than cost, being able to store and ship gases in liquid form becomes important.

Neon has been tested enough to establish its safety and usefulness, and has also been used at sea in specially monitored working dives to as deep as 640 fsw. In theory, neon ought to have better decompression properties than either helium or nitrogen, but research to establish this in practice has not yet been completed. That decompression from neon can safely be carried out has, however, been established.

D. Hydrogen

Up to a decade ago, research on hydrogen-oxygen breathing mixtures for use in deep diving was discouraged for reasons of safety. Since that time, human and animal studies in test chambers have shown that mixtures of up to 4 or 5% oxygen in hydrogen are completely safe with respect to flammability and explosive hazards. The operational use of hydrogen in diving requires adequate safety procedures, similar to those which are used for other dangerous materials in diving.

Hydrogen is the only oxygen diluent which can replace helium as a breathing mixture over the entire depth and time spectrum of deep diving operations. At present, operations using helium require large on-board supplies of gas, which cause logistical problems; because the constituents of hydrogen-oxygen breathing mixtures may be obtained directly from sea water, it should be possible to synthesize the breathing mixture at the diving site. This technique would eliminate problems of storage, handling, and transportation, and would considerably lessen the cost of gas.

Research on hydrogen has yielded the following findings:

1) Based on pulmonary function measurements, hydrogen has a 2:1 depth advantage over helium.

2) Voice distortion is no greater with hydrogen than with helium, and unscramblers ought to work as well for hydrogen as for helium, especially where the ratio of inert gas to oxygen is the same.

3) Thermal problems appear to be about the same for hydrogen as for helium.

4) Manned studies at 7 ATA have shown no decrement in performance with hydrogen, as compared to those with helium-oxygen mixtures. More work needs to be done to determine whether hydrogen has narcotic or neurologic effects.

5) Decompression with hydrogen appears to be slightly more difficult than with helium.

To date, there are no medical contraindications to the use of hydrogen-oxygen breathing mixtures, within the limits of the research which has been done. In essence, hydrogen appears to be a feasible replacement for helium which may even offer some operational and physiological advantages.

E. Multi-Gas Mixtures and Gas Sequencing

Switching from one breathing gas to another during a dive and using breathing mixtures composed of several gases are operating techniques which are used to reduce costs, improve decompression, reduce chilling, improve voice, and lessen the effects of HPNS. They may simplify or complicate operations. Despite the fact that gas sequencing and multi-gas mixtures are commonly used in operational diving, very little research has been done on the biochemical and physiological effects of these techniques. Both the basic mechanisms and practical effects urgently need investigation.

A few examples of the use of these methods in commercial diving are listed below; these are reports from the field, and should not be interpreted as research findings.

1. Most diving companies shift to air at some point in the decompression, usually in the range of 100-150 fsw; this switch is often timed to coincide with the transfer of divers from the bell to a larger chamber, so that part of the chamber complex can be filled with air instead of helium.

2. Mixtures of helium and oxygen which are richer in oxygen than the bottom mix, and which may also contain added nitrogen, are used during commercial gas sequencing.

3. When a diver saturated with a helium mixture breathes a denser gas like nitrogen, he may suffer vestibular decompression sickness; if he is immersed in helium, skin lesions and itching may occur. This phenomenon is called counter-diffusion.

4. Decompression sickness appears to be more likely soon after a gas switch.

5. The use of sequencing, often involving unusual gases such as argon or neon, seems to make a faster rate of decompression possible.

6. Use of a mixture containing five different inert gases has allowed immediate decompression from 180 minutes at 60 fsw, in contrast to the normal limit for an air dive without decompression sickness, which is 60 minutes at that depth.*

F. Other Gases

There are several other gases which have properties that make them feasible for diving, particularly as small fractions of the breathing mixture, but it seems unlikely that any gas other than helium, nitrogen, hydrogen, or neon, will be the principal gas in deep diving. Minor component gases will be used to improve decompression, voice, and resistance to HPNS, and may be useful for other physiological reasons. These minor gases are very important, however, in research on gas transport, decompression, breathing mechanics, narcosis, and other aspects of diving physiology.** There is also a possibility that liquids may be used as a breathing medium under certain conditions.*** However, considerable research is needed before liquid breathing will be commercially feasible.

VI. REQUIREMENTS AND PRIORITIES

A. Conservation of Helium as a Resource

1. In the opinion of this panel attention must be directed toward minimizing waste of our nation's limited and irreplaceable helium resources, in particular the loss of helium as a minor component of natural gas. Helium resources appear large in relation to present requirements, but are marginal if future requirements are considered.

2. Increased attention should be given to methods for using such helium resources as are available with the greatest possible efficiency, including recapturing and storing helium in the field, and reclaiming it for further diving operations. This might call for a revision of current contracting practices, and should include efforts to provide safer, smaller, more reliable, more efficient, and above all less expensive machinery for recapturing, storing, and reclaiming used helium. The development of efficient and operationally satisfactory closed-circuit breathing gear, both self-contained and chamber-based, must also be encouraged.

---

*G. F. Bond, F. L. Fishbach, M. W. Lippitt, R. D. Woodson. (in preparation) Multiple Inert Gas Transport Patterns. Navy Coastal Systems Laboratory.

**These gases include argon, methane and other hydrocarbons, CF_4 and other freons, nitrous oxide, and sulfur hexafluoride.

***For a discussion of liquid breathing, see Appendix A, Report 4.

B. Biomedical Research

1. Decompression

Valid methods for comparing gas mixtures involving different principal inert gas constituents need to be developed. Such comparisons should be carried out under controlled conditions using operationally meaningful but carefully standardized exposures. Data are needed on short-duration working dives to modest and maximal depths, and saturation exposures at several pressures. These data might also be useful as a base for the prediction of accurate decompression schedules.

The primary emphasis in these studies should be on the signs and symptoms of acute decompression sickness, but there is also a need for studies to assess delayed or long-term decompression injury, such as aseptic bone necrosis. These studies should investigate profiles which produce acute decompression sickness, and those which give rise to marginal or chronic symptoms.

In addition to investigating the potential use of gases other than helium as primary constituents of diving atmospheres, there is a need to explore their use as components in multi-gas mixtures and in gas sequencing procedures designed to achieve more rapid and safer decompression.

2. Effects on the Central Nervous System

a. Comparative narcotic potency

Reasonable data are available for a quantitative comparison of helium and nitrogen, but present information on neon, neon mixtures, and hydrogen is inadequate, and experiments to fix a numerical value for their relative narcotic potencies are indicated. Experiments in humans to determine the relation between partial pressure and behavioral impairment are needed for all diving inert gases and gas mixtures. This is of particular significance in the case of hydrogen, since it may play a major role in very deep diving operations because of its specific anti-HPNS and favorable mechanical properties.

b. Interaction with HPNS

The HPNS properties of gases other than helium should be studied, as well as the anti-HPNS effects of other inert diving gases. These studies are needed to correlate partial pressures and symptoms. Work should also be done to determine the degree of interaction with other factors, such as rate of compression and duration.

3. Miscellaneous Effects

There are a number of physiologic effects which reflect differences in the physical characteristics of different gases. The following deserve study:

1) Estimates of the thermal effects of different gases or gas mixtures on heat loss, as well as studies on temperature perception, thermal comfort, and the distortion of thermal gradients within the body.*

2) Effects on gas exchange in the lungs, with particular emphasis on possible changes in blood oxygenation at high pressures, effects on respiratory work at high pressure both in freely-breathing subjects and subjects using different types of breathing apparatus.**

3) Studies of possible toxic effects of gases, with emphasis on prolonged exposures, and using hematologic and biochemical methods to detect marginal changes which could become important in extreme exposures.

4) Studies of gas effects on voice communication to determine whether the presently used helium unscramblers can be utilized in hydrogen atmospheres. Further studies are also indicated to determine a more precise relation between neon content and the intelligibility of voice communication, and on the use of other additives, such as CF_4.

C. Operational Aspects of Gases Other Than Helium

1. Economic feasibility studies are needed to determine and recommend optimal methods of supply and distribution of alternative gases, particularly neon and hydrogen, and the anticipated costs at various levels of total and of local utilization.

2. The introduction of alternative gases in future diving operations may require and benefit from significant improvements in current methods of handling gases at sea. Such improvements may involve the development of economical methods for on-site preparation of gas mixtures, so that flexible operations can be maintained without sacrificing safety.

3. Analytical methods

Analytical and control capability need to be developed, with particular emphasis on simplified methods to determine chamber inert gas composition in the field. Monitoring equipment is needed, so that experience with unusual mixtures is not lost, particularly information on decompression.

---

*For a discussion of thermal problems, see Report 14.

**For a discussion of respiratory problems in diving, see Report 4.

D. Priority Categories

The panel has reviewed the various problems of action outlined in this report; these can be divided into the following categories, in order of decreasing priority.

Category I.

a. Conservation of helium resources

b. Optimization of helium use at sea

Category II.

a. Comparison of decompression properties

b. Decompression properties of multi-gas mixtures and gas sequencing

c. Interaction of various gases with HPNS

d. Effects of various gases on respiratory work

Category III.

a. Residual gas-related decompression effects

b. Comparison of narcotic potencies

c. Thermal properties

d. Economic feasibility studies

Category IV.

a. Minor components and exotic gas additives

b. Effects on gas exchange in lungs

c. Shipboard handling procedures

d. Special analytical and monitoring techniques

VII. FACILITIES

The committee has not listed facilities separately, because any laboratory involved in decompression work is equipped to do the research suggested in this report.

PHYSIOLOGICAL AND TOXIC EFFECTS OF RESPIRATORY AND CONTAMINANT GASES

(ACUTE AND CHRONIC)

Part #9 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Karl E. Schaefer, M.D. (Chairman)
Chief, Biomedical Sciences Division
Naval Submarine Medical Research Lab
Naval Submarine Base, New London

Lt. Melvin E. Andersen, MSC, USN
Toxicology Division, Environmental
Biosciences Dept.
NMRI

Peter B. Bennett, Ph.D.
Co-Director, F. G. Hall Environmental
Research Lab
Director, Diving Research Program
Duke University Medical Center

Robert W. Hamilton, Ph.D.
President, Tarrytown Labs, Ltd.

Charles Hedgepeth
Operations Manager, Ocean Systems, Inc.
Reston, Virginia
A.D.C. Representative

TABLE OF CONTENTS and Organization for part 9

Physiological and Toxic Effects of Respiratory and Contaminant Gases

I. DESCRIPTION OF THE PROBLEM 1

A. General Concept of Limits

B. Respiratory Gases

1. Oxygen
2. Carbon Dioxide
3. Heat and Gas Exchange
4. Respiratory, Blood and Tissue Gas
5. Water Vapor

C. Inert Gases

1. Nitrogen
2. Helium
3. Other Gases

D. Potentially Toxic Hyperbaric Contaminants

1. Carbon Monoxide
2. Oil and Aerosols
3. Halogenated Hydrocarbon
4. Habitat Gases
5. Pyrolysis and Welding Products
6. Body Wastes
7. Others

II. OPERATIONAL DIVING 13

A. Modes of Diving

1. Air Diving
2. Mixed-Gas Diving
3. Saturation and Excursion Diving

B. Mode-Related Physiological and Toxicological Problems

1. Air Diving

   a. Nitrogen narcosis
   b. Oxygen
   c. Carbon dioxide
   d. Contaminants

            1) Low-pressure compressor
            2) High-pressure compressor

    2. Mixed-Gas Diving

        a. Oxygen
        b. Carbon dioxide
        c. Helium
        d. Trimix
        e. Contaminants

    3. Saturation and Excursion Diving

        a. Oxygen
        b. Carbon dioxide
        c. Water vapor
        d. Inert gas
        e. Contaminants

III. PROBLEMS TO BE SOLVED 20

    A. General

    B. Oxygen

    C. Carbon Dioxide

    D. Inert Gases

        1. Nitrogen
        2. Neon, Hydrogen, and Other Inert Gases
        3. Helium
        4. Physiological Detection
        5. Toxicity of Contaminants

IV. FUTURE REQUIREMENTS 25

V. PRIORITIES

    A. Short-Term Priorities

        1. Education and Training
        2. Evaluation, Testing, and Improvement of Equipment
        3. Improved Information Exchanges
        4. Research to Establish Limits

    B. Long-Term Priorities

VI. RESEARCH FACILITIES 26

I. DESCRIPTION OF THE PROBLEM

A. General Concept of Limits

During underwater operations, divers are exposed to increased barometric pressure which directly affects the mechanics and physiology of respiration and particularly the respiratory gases. The purpose of this study is to delineate the physiological and toxicological effects of respiratory and contaminant gases under acute and chronic conditions of exposure.

At the outset, it should be pointed out that gross deviations in many of the gases discussed in this section have been the cause of too many serious accidents, including many fatalities. Accordingly, we are concerned with both the acute, short-term life-sustaining situation as well as with more subtle long-term hazards.

The concept of limits, therefore, takes on a double meaning: 1) what is necessary to maintain life, consciousness, effectiveness, and well-being immediately, and 2) what environmental variables and levels of variables may constitute a long-term threat. The former concern is the topic of respiration and environmental physiology, while the latter belongs to the field of toxicology.

Attempts to establish limits of gas pressures or environmental contaminants are based on the concept of threshold-limit values (TLV), a concept which has undergone changes with time. Originally, threshold limit values were determined when pathological changes were found in histological examinations of the tissues of exposed animals; later, biochemical parameters which proved to be more sensitive were added, and most recently, behavioral parameters have been included. As a consequence, the threshold limit values for various contaminants have been reduced over the years.

Different attitudes towards threshold limit values prevail in different countries, e.g., Russia has much lower threshold limit values than the U. S. However, experts of the USSR will agree that these threshold limit values are so low that they are beyond practical realization since environmental and particularly atmospheric control has not reached the necessary state of perfection.

Threshold limit values for an average industrial 8-hour per day exposure are higher than those for continuous exposure for 90 days, e.g., the TLV values used in submarines. During diving operations involving habitats on the continental shelf, the added effect of increased pressure has to be taken into account in determining limits.

Adaptation and tolerance limits for respiratory gases like O_2 and CO_2 are important. As an example, a concept of triple tolerance limits for chronic CO_2 toxicity at normal atmospheric pressure has been advanced for three different levels of activity: 1) CO_2 levels above

3% produce performance deterioration and alteration in basic physiological function; 2) a 0.8-1.5% level of CO_2 does not affect basic physiological functions and performance, but does initiate long-range adaptive processes; and 3) a CO_2 level below 0.5-0.8% causes no significant physiological or adaptive changes. (18). In addition, individual differences in tolerance to increased levels of O_2 and CO_2 play a significant role in the ability of different divers to adapt to diving operations. These introductory remarks should emphasize the difficulties in establishing straightforward and rigid standards for respiratory and contaminant gases.

B. Respiratory Gases

This section considers the primary gases involved in human respiration: oxygen, CO_2 and water vapor. These are treated separately because of their importance in all diving situations. Tolerance levels are given as guidelines only.

1. Oxygen

Oxygen is the princess among gases. It is essential at a proper level to support life, becomes toxic in several ways in excess, and as a component of compressed gas or in chambers it increases the risk of fire. Oxygen is an essential component of breathing gas. When it is lacking, hypoxia results. Its respiratory effectiveness is a function of its partial pressure; like other such factors, the effects are very sensitive to the time of exposure. Expressed in sea level terms, a person experiences dizziness, euphoria and light-headedness when the inspired percentage is reduced from 21% to about 15% (abruptly), or expressed as partial pressure, reduced from 0.21 to 0.15 ATA. Further reduction increases these effects and results in increased breathing, blurred or tunnel vision and motor impairment, similar to drunkenness; unconsciousness occurs at the level of 7-10% in most individuals. Further reduction will cause death, though the level at which this occurs is very much affected by the duration of exposure and individual tolerance; it is generally between 3 and 6%. A particularly insidious aspect of hypoxia is the prevalence of euphoria, which can cause a diver to ignore warning signs and fail to take corrective action until it is too late.

Excess oxygen is toxic. Short-term exposures (minutes to a few hours) to partial pressures greater than 3 ATA can cause epileptic-like convulsions. These can cause drowning or injury; there is however no evidence that they cause permanent neurological damage. Longer exposures to lower levels, perhaps to 0.7 ATA or more for several hours, can cause lung damage. Still longer exposures (weeks) at still lower levels will cause an adaptive reduction in red blood cells. Long-range effects of high oxygen levels are undetermined, but there is no reason to believe they can safely be disregarded. One study implicates certain high-oxygen exposures in future cardiovascular disease.

Although diving operations are presently designed with the effects of oxygen in mind, they could be made safer and more cost-effective by a better understanding of oxygen toxicity, its mechanisms, prevention, and treatment. This is particularly true of extended air-diving operations, since the oxygen content of air cannot easily be reduced. Also, even though research has greatly reduced the incidence of fire, divers are still dying in chamber fires. (Oxygen and its effects are covered in more detail by committee #10).

2. Carbon Dioxide

Respiratory limitations and associated CO_2 retention have been found during exposure to very high pressure while breathing helium-oxygen gas mixtures, but only during heavy exercise. CO_2 retention and a reduction in ventilation are observed during heavy exercise while breathing air at 4 ATA both in short-exposure experiments and in air saturation experiments.

Although underwater breathing equipment has improved considerably over the years, divers still experience difficulties during deep dives (3). Serious respiratory limitations were encountered with different types of underwater breathing equipment during the SEALAB III experiment both in the 1010-fsw (31·5 ATA) open-sea dive and in a 640-fsw (20·4 ATA) open-sea dive using neon. In the SEALAB III experiment, the divers were thermally unsupported and were working from a depth of 620 fsw (19·8 ATA) breathing helium-oxygen with equipment which did not allow them to get enough gas.

Carbon dioxide accumulation in the body has severe effects on thermoregulation. Body heat production is impaired and heat loss increases at higher CO_2 concentrations (14). In the 1010-fsw (31'5 ATA) open-sea dive the divers were thermally supported but encountered respiratory difficulties even during minimal exercise using an open-circuit, demand-type mask. Laboratory tests carried out with the same mask showed that the level of mechanical work required while breathing dense gas with this equipment was extremely high. In the 640-fsw (20·4 ATA) open-sea dives neon-oxygen mixtures were used as breathing gases with the same type of mask. During the working dives at this depth, the divers probably had substantial CO_2 buildup but did not recognize this condition. Inspired oxygen was rather high (1·6 ATA), which may have contributed to CO_2 retention.

The physiological effects of underwater breathing equipment on ventilation and gas exchange have to be taken into consideration, and methods for testing the physiological effects of underwater breathing apparatus have been proposed. At the U.S. Navy Experimental Diving Unit, tests on breathing equipment have been performed at different working depths. Safe limits for arterial blood PCO_2 was set at 50 mmHg, and if higher levels of CO_2 were reached, the equipment was considered unsafe (21). Since a good percentage of divers retain CO_2 and have CO_2 levels as high as 50 mmHg even when they are breathing room air, the validity of the proposed physiological criterion for the testing of underwater breathing equipment is questionable. Detailed studies on the effect of underwater breathing equipment on the mechanics of respiration, respiratory and blood gas exchanges are clearly needed.

Plans for exploration of the continental shelf have focused more attention on shallow-habitat air diving recently. Following Project TEKTITE, a number of other studies supported by NOAA (NOAA OPS I and II were undertaken at Tarrytown). Two 30-day studies using compressed air at simulated depths of 50 and 60 feet of sea water (oxygen partial pressures 0·52 ATA and 0·59 ATA, respectively) were recently carried out without medical complications at the U.S. Naval Medical Research Lab, Groton, Connecticut.

Acid-base balance data obtained during the 60-fsw dive (2·8 ATA) produced evidence of mild respiratory acidosis lasting from the second week of exposure to the end of the experiment. Exercise loads of 150 watts which produce an oxygen consumption above 2.0 liters/min were found to result in CO_2 retention and reduction of ventilation at 90 fsw while breathing air during a saturation dive. Studies on the limits of exercise loads in air-saturation diving are of both practical and theoretical interest, and they should be extended.

The role of carbon dioxide in inert gas narcosis has also received more attention in recent years, since it plays an important role when the limits of air diving are approached (2). Hesser, Adolfsen and Fagraeus (9) attempted to delineate the nitrogen and CO_2 components in compressed air narcosis and found that high alveolar N_2 and CO_2 pressures are additive in their effects on performance; below 40 mmHg, the CO_2 component is negligible. This investigation enlarged on the earlier observations of Case and Haldane (4), who concluded that CO_2 might not cause, but might well enhance, the development of nitrogen narcosis. Severinghaus (19) recently discussed the problem of CO_2 narcosis on the basis of data obtained in experiments with volunteers in which the anesthetic potency of CO_2 was determined by titrating CO_2 against N_2O (10).

CO_2 narcosis effects have been related to extracellular pH (6). The lipid-like anesthetic activity of CO_2 has not been tested because it seems to produce acidotic anesthesia at much lower levels.

The respiratory response to CO_2 and the control of ventilation at high pressure have been the subjects of a few investigations which showed that the reduction of ventilation found in CO_2 response curves under increased pressure was due to increased gas density and breathing resistance.

A thorough study measuring CO_2 response curves without using respiratory masks, which introduce increased breathing resistance, needs to be undertaken.

CO_2 retention occurs frequently during exercise at high ambient pressure. The ventilatory limitation in heavy physical work is one of the primary factors determining the depth limit in practical diving operations. Because of the increased density of the inspired gas, the work of breathing is increased, resulting in a decrease of alveolar ventilation and CO_2 retention. It is well known that the latter may be hazardous or fatal for a diver. What is not generally known is that CO_2 accumulation may in fact occur in a diver breathing at a frequency several times faster than normal, i.e., apparently hyperventilating. Hyperventilation washes CO_2 out of the lungs and blood under normal conditions. This causes a physiological reduction in brain blood flow, and leads to dizziness and unconsciousness. This paradox is thought to be due to rebreathing of dead space air, but detailed experimental verification of this hypothesis is totally lacking.

Fig. 9-1. shows CO_2 retention in exercise at increased ambient air pressures.

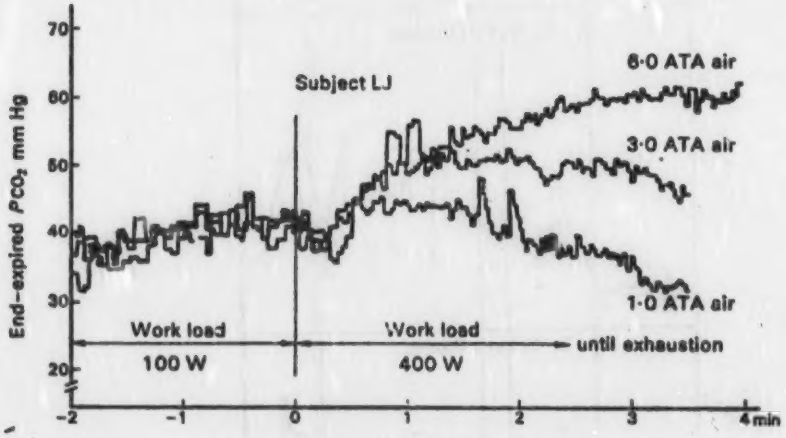


Fig. 9-1. Typical time course of breath-by-breath end-expired PCO_2 during submaximal and maximal exercise at 1·0, 3·0 and 6·0 ATA air. (After Fagraeus & Linnarson 1973).

These values are from unencumbered subjects; breathing through a diving mask causes much higher CO_2 buildup. Trained divers have a tendency to retain CO_2 instead of increasing their ventilation sufficiently to meet the demands of exercise. This form of adaptation to CO_2 in divers and its influence on cardiopulmonary efficiency in exercise at increased pressure requires more research.

Another important aspect of CO_2 in diving is its role in continuous exposure to a high-pressure helium-oxygen environment. Data from a case of continuous hyperventilation during a helium-oxygen saturation dive to 1000 fsw are presented in Fig. 9-2 to

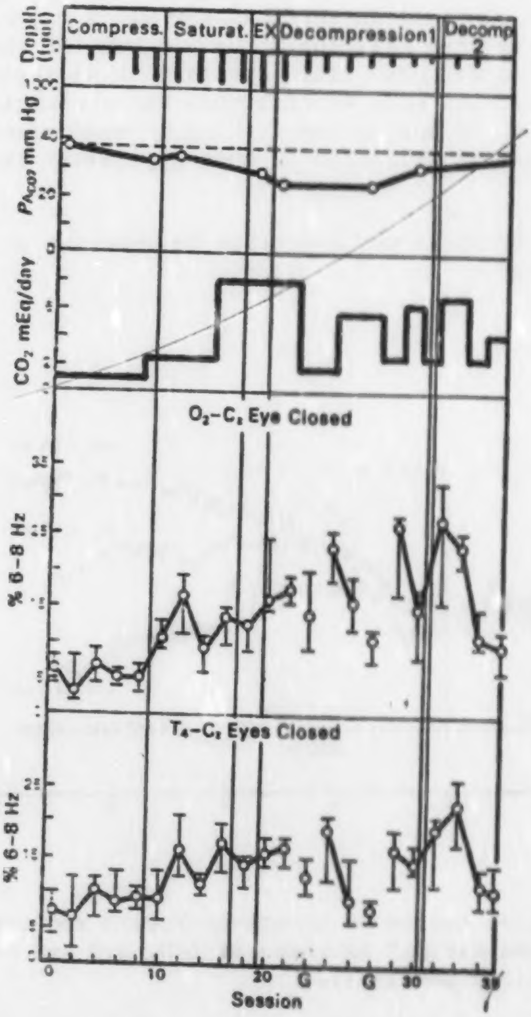


Fig. 9-2. Subject C.D. Time course in alveolar carbon dioxide tension, urinary CO_2 excretion and EEG changes (percentage 6-8 Hz frequency), two electrode positions O_2-C_z and T_4-C_z, eyes closed. (After Proctor et al. 1972).

demonstrate that hyperventilation can lead to decreased alveolar CO_2 tension and brainwave changes under these conditions. This state of chronic hyperventilation is known to lead to increased oxygen consumption and metabolic changes involving increased lactic acid production, and sensitivity to stress. Buehlmann considers hyperventilation of divers dangerous and makes a special point of training divers to avoid it.

3. Heat and Gas Exchange under Increased Pressure Using Different Gas Mixtures

Both CO_2 and helium are known to have profound effects on heat loss and both have been implicated in fatal accidents such as those which occurred in SEALAB III and the Johnson-Sea-Link. Heat and gas exchange under increased pressure using different gas mixtures require systematic study.

4. Respiratory, Blood and Tissue Gas Exchange During High Pressure Exposure

The lack of quantitative data on respiratory, blood, and tissue gas exchange for different diving modes has hindered urgently needed progress in planning decompression tables. Moreover, rapid changes of breathing mixtures during decompression have proved to be hazardous on many occasions. With the advent of mass spectrometry it is possible to obtain quantitative data on O_2, CO_2, and inert gas exchange in respiration, blood and tissues. A systematic study of these problems is required.

5. Water vapor

Normally, each inspired breath is moisturized on its way to the lungs, but an especially dry breathing gas will cause irritation and discomfort in time. Breathing gases high in or saturated with water vapor poses no particular problem. However, when the whole body is in a humid environment, thermal balance is difficult to maintain, infections are almost inevitable, and some researchers believe that decompression sickness is more likely to occur. A particular problem of saturation diving is "swimmer's ear", a bacteriological infection of the ear canal which can bring an entire diving operation to a standstill. Extended exposure to wetness can cause excessive tenderness of skin, predisposing the diver to injury and infection.

C. Inert Gases

Because of the toxicity of oxygen at increased pressures, and because a diver must breathe gases at the pressure of the water surrounding him, inert gases are used in diving as a diluent for oxygen. Air contains 79% nitrogen; it is of course the basic diving gas. This section discusses the toxic effects of the inert gases currently used in diving, including nitrogen. Relative potencies of these gases are given in Table 9-1.

Table 9-1. Correlation of Narcotic Potency of the Inert Gases Hydrogen, Oxygen and Carbon Dioxide with Lipid Solubility and other Physical Characteristics.

Gas	Molecular weight	Sol. in lipid	Temp., °C	Oil-Water sol. ratio	Relative narcotic potency
					(least narcotic)
He	4.0	0·015	37°	1·7	4·26
Ne	20.0	0·019	37·6°	2·07	3·58
H_2	2.0	0·036	37°	2·1	1·83
N_3	28.0	0·067	37°	5·2	1·00
A	40.0	0·14	37°	5·3	0·43
Kr	83·7	0·43	37°	9·6	0·14
Xe	131·3	1·7	37°	20·0	0·039
					(most narcotic)
O_2	32	0·11	40°	5·0	
CO_2	44	1·34	40°	1·6	

1. Nitrogen

It has been known for many years that divers and others breathing compressed air experience a sense of intoxication and loss of judgment with numbness, poor coordination, amnesia, and other mental effects. These effects are due to the narcotic action of the nitrogen component of air. Detectable at about 4 ATA (100 feet of sea water), the effects become increasingly debilitating with increasing depth. Normally, air diving is considered safe to 150 fsw, and for short times and under exceptional conditions to perhaps 250 fsw. The degree of narcosis varies with the individual as well as with other conditions such as temperature, CO_2, work level, and time of exposure. Recent reviews of this subject are available for additional details (1, 2).

A similar narcosis is caused by certain other "inert" (non-metabolic) gases, and by gaseous anesthetics. The narcotic potency of the different gases and anesthetics increases with increasing lipid solubility. The mechanism of nitrogen narcosis is undoubtedly the same as that of the gaseous general anesthetics. One convincing theory is that anesthesia results from a change in cell membrane permeability as a result of the absorption of the anesthetic gas by the lipid of the membrane and its consequent swelling. This theory is closely related to hypotheses dealing with the High Pressure Nervous Syndrome.

A significant aspect of nitrogen narcosis is the ability of divers to adapt to it. Adaptation is manifested in two ways. Divers working during deep, long air dives on several successive days feel somewhat less narcosis on each suceeding day. This effect, if maintained, can add perhaps 50 feet to the safe diving depth. Some divers exposed continuously to high levels of nitrogen under saturation diving conditions exhibit another form of adaptation. Acclimatization apparently allows a diver to dive an additional distance about equal to the distance he could normally dive from the surface, if he has adapted to the saturation or habitat depth. That is, a diver saturated at 100 fsw might be able to dive to 250 fsw safely, if he could normally make a safe 150-fsw dive from sea level. The full implications of this phenomenon are only partly understood, but the prospects are most promising: extensive diving work could potentially be done at 250 fsw using nitrogen-based mixtures, whereas presently all work at that depth must be done with helium-oxygen mixtures.

2. Helium

Helium exhibits no narcotic properties. However, partly as a consequence of its non-narcotic properties, compression to very high pressures with helium does result in the signs and symptoms of HPNS with resulting performance decrement. This is a function of the increase in hydrostatic pressure. Addition of a narcotic, such as nitrogen, counteracts the effects of pressure and ameliorates or prevents the signs and symptoms of HPNS.

3. Other Gases

Other gases which are seriously considered for use in diving are neon, hydrogen, and argon. Of these, neon, like helium, causes no narcosis at depths as great as 1200 fsw, but neon is too dense to consider for use as a breathing gas much beyond 600 fsw. Argon appears to be about twice as narcotic as nitrogen, and hydrogen less than half so. Other gases used in diving research or for special purposes (e.g., to improve voice transmission) are sulfur hexafluoride (SF_6), CF_4, methane, nitrous oxide, and krypton. These all exert narcotic effects at least as great as those of nitrogen. Research to date indicates that none are otherwise toxic. Characteristics of the various inert gases are considered in more detail by the committee on the Use of Gases other than Nitrogen and Helium.

D. Potentially Toxic Hyperbaric Contaminants

Many potentially toxic vapors and gases have been identified in various diving environments. Although most of these are present in concentrations lower than those concentrations which produce overt toxicity at 1 ATA, the potential for exposure of divers to harmful levels does exist. Unfortunately, with the exceptions of carbon monoxide and sulfur dioxide, there is no published research on the acute hyperbaric toxicity of these gases, and without exception, nothing has been published on their chronic toxicity under hyperbaric conditions. In outlining the established toxicity of these substances, it is therefore necessary to describe the effects that are observed at 1 ATA.

1. Carbon Monoxide

Carbon monoxide is a frequent contaminant of compressed air used by divers as a breathing gas. Small amounts are produced during normal metabolism in man, and CO can therefore be introduced into the deep sea habitat by the divers themselves. CO is produced by fires, and can be formed in substantial amounts during the normal metabolism of methylene chloride, a commercially important solvent. At high concentrations it causes death from anoxia by competing with oxygen for the available hemoglobin. At lower levels it compromises the ability of the organism to deliver oxygen to the tissues by binding to a portion of the available hemoglobin. On extended exposures this toxic effect is partially compensated for by an increase in the number of circulating red cells. Exposure to lower levels of carbon monoxide also produces neurological, behavioral, and other cardiovascular toxic effects. Smokers normally have elevated levels of blood carboxyhemoglobin and divers who smoke may therefore run a greater risk of carbon monoxide toxicity than non-smokers. The acute toxicity level of carbon monoxide, measured as the amount of carbon monoxide required to kill an animal, has been determined at various pressures (13). Its lethality was found to depend on its partial pressure alone, and not on the total pressure. Whether this is true of non-lethal acute hyperbaric CO toxicity, or of chronic hyperbaric CO toxicity is unknown. The problem of compressed air contamination by carbon monoxide and other materials such as sulfur oxides, nitrogen oxides, and hydrocarbons, all of which are found in the compressor exhaust of the gasoline or diesel-driven air compressors, demands careful attention. The toxicity of at least two of these combustion products, carbon monoxide and sulfur dioxide, is proportional to partial pressure. At depth therefore contaminated compressed air will be correspondingly more toxic than at pressures of 1 ATA.

2. Oil and Aerosols

Lubricating oil and the mist (aerosol) formed by this oil are other common contaminants of compressed air. Although oil is not normally particularly toxic, these oil aerosols cause pneumonitis, oil pneumonia and paraffinoma at sufficienty high levels. In addition to the direct toxic effects of the oil-mist aerosol, both oil and water aerosols present certain other toxicological problems. They can dissolve or adsorb non-volatile materials, and then deliver these non-volatiles to the lungs. This mechanism can produce toxic body loads of a substance which could not have reached toxic levels by vapor inhalation alone. High humidity favors the formation of water aerosols and this tendency is another problem of water-saturated atmospheres. Fortunately, aerosols are easily removed by electrostatic precipitators or appropriate filters.

3. Halogenated Hydrocarbons

In the last several decades these man-made chemicals have found numerous commercial applications. They are used, for instance, as refrigerants, propellants in aerosol cans, fire extinguishing agents, and anesthetics. They have been identified as trace contaminants both in space cabin atmospheres and in submarines. Although very great differences in toxicity exist among various halogenated hydrocarbons, some generalizations as to the toxic effects of these chemicals can be made. At high concentrations halogenated hydrocarbons are anesthetics, and on acute exposure they cause death by central nervous system depression. At lower levels many of these materials, such as bromobenzene, carbon tetrachloride, and vinylidene chloride, cause severe liver damage. With all three of these materials, however, it is not the parent compound but a metabolite that is toxic to the liver. Degree of liver damage is influenced by nutritional status. The fasted rat is more susceptible apparently because its liver is depleted of glutathione which can block the toxic effects of these metabolites.

In addition to nutritional status, stress can also alter the toxicity of halogenated hydrocarbons. Upon exposure to certain freons, the heart is sensitized to epinephrine-induced arrythmias. The diseased heart appears to be more susceptible to these arrythmias than the healthy heart. Interactions between toxicity and nutritional status and toxicity and stress may be important in divers exposed in deep sea habitats for long periods. The toxic effect of freons on the heart may be related to the anesthetic properties of these halogenated hydrocarbons. Certain general anesthetics are less effective at pressure, and it is possible that the anesthetic effects of the freons are also reduced at pressure. This difference in potency of certain drugs at elevated pressures indicates the danger of assuming that all forms of toxicity are pressure-independent. There is at present no way of determining whether this is true except by direct experimentation.

One particularly insidious form of halogenated hydrocarbon toxicity has been documented for vinyl chloride. Exposure to this substance has been associated with the appearance in man and in rats of a rare form of liver cancer, angiosarcoma. These tumors can occur a very long time after exposure, even though the exposure itself caused no overt toxicity. It must be emphasized that tumor formation is an established toxic effect for only a few halogenated hydrocarbons, and not a characteristic of this entire family of chemicals.

4. Habitat Gases

Most polymeric plastics are manufactured from halogenated hydrocarbons or hydrocarbon monomers. Residual monomer can slowly bleed out of the polymer into the environment. These off-gassing products, combined with vapors from solvents, glues, and other materials used in diving hardware, are here grouped together as "Habitat Gases". In closed environments these gases can accumulate to significant levels if not properly removed. Removing these contaminants must be considered both in the design of life-support systems and in the search for new materials to replace plastics which produce significant levels of contaminants by off-gassing. Off-gassing can also become a problem when contaminant gases are leached from hoses supplying breathing air to divers.

5. Pyrolysis and Welding Products

In addition to pre-existing contaminants of the diving environment, the elevated temperatures of welding and fires in the closed environments produce a number of toxic by-products. Fires produce corrosive gases (nitrogen oxides, sulfur oxides, hydrogen chloride, hydrogen fluoride, and hydrogen cyanide), many partially oxidized products (dehydrogenated hydrocarbons and carbon monoxide), and free radicals. Smoke, a complex particulate mixture, is very toxic, especially to the lung. The exact composition of the fire atmosphere depends among other things on the temperature of the fire, the oxygen concentration supporting the burn, and the material being consumed. The use of some materials, for instance polymers which produce large amounts of hydrogen cyanide upon burning, should be avoided whenever the danger of fire exists. Another problem of the fire atmosphere is the enormous potential for interaction—interaction among various contaminants, between temperature and contaminants, and between the physiologic gases, carbon dioxide and oxygen, and the contaminants. The study of fire toxicology has only recently begun to receive the attention it deserves. Welding also produces a complex toxic atmosphere, containing smoke, carbon dioxide, water vapor, ozone, nitrogen oxides, and probably metal vapors and metal particulates. The chronic toxicity of these mixtures has not been determined, yet divers are frequently required to weld in closed environments.

6. Body Wastes

As in any closed environment, extended habitation at pressure requires consideration of adequate methods to remove body wastes from the habitat. Fecal and urinary wastes are readily flushed from the environment, but gaseous wastes, carbon dioxide, carbon monoxide, hydrogen sulfide, methane, ammonia, and others, must be managed by adequate scrubbing of the atmosphere. These wastes are toxic in sufficient concentrations, and many have disagreeable odors which can also interfere with the efficiency of the divers.

7. Others

This list is not, and indeed cannot, be considered exhaustive. The toxicity of many materials is obviously not yet fully appreciated, and new materials are constantly being introduced. Furthermore, in addition to the environmental toxicants encountered by divers in breathing gases and closed habitat systems toxic agents may also be present in their work environment. Examples of this include salvage work with ships laden with chemical cargoes, work in and around areas of extensive oil-spills, and work in heavily polluted waters.

II. OPERATIONAL DIVING

This section deals with diving as it is actually practiced so that problems relating to physiological and toxic effects can be keyed to real-world diving activities.

A. Modes of Diving

1. Air Diving

Overwhelmingly the most important and prevalent type of diving, air diving, may be done with SCUBA gear or by means of surface-supplied compressed air. Typically, air-diving is used for work to depths of 150-180 fsw, but may be extended on occasion to work at perhaps 250 fsw.

2. Mixed-Gas Diving

In this category we include all short-term diving which involves the use of mixtures other than atmospheric air. The most important type here is deep helium-oxygen diving. Heliox diving covers the range below the level where air can be used, to as deep as decompression procedures, equipment, and job demands will allow--currently the range from 150-500 fsw. As bottom time extends beyond about one hour, at the deeper end of the range, the procedures change to saturation diving, but that distinction is not particularly relevant here.

Deep heliox diving is most often done by getting the diver out of a bell or submarine into the water. However, up to about 300 fsw diving can be done safely using classical hard-hat gear over the side. More often, light open-circuit demand gear is used.

Another mixed-gas method is to enrich air with extra oxygen to permit longer bottom times at relatively shallow depths. This method therefore has both the nitrogen and oxygen characteristics of air diving and the "mixture" characteristics of mixed-gas diving.

Still another variation, and one with more future potential than present application, is the use of partial or full rebreathers (also called semi-closed or closed systems). These units are usually backpacks with some mechanism for providing a proper breathing mixture. An expansion of this concept is the "push-pull" system, which recirculates the bell environment to and from the diver.

3. Saturation and Excursion Diving

Saturation diving is justified because it eliminates the need for frequent decompression. In saturation diving, the divers live in a "habitat" overnight between work shifts, with the habitat maintained at a pressure greater than atmospheric. The habitat may be on the sea floor, but in commercial work is usually on the deck of the drilling rig or work barge. Pressure at the working depth may be greater than that in the habitat, in which case the divers make pressure or depth "excursions" to and from the work site. Where the working depth permits, the habitat may well be filled with a nitrogen-oxygen mixture, or even air.

B. Mode-Related Physiological and Toxicological Problems

1. Air Diving

a. Nitrogen narcosis

The depth limitation of air diving is largely due to nitrogen narcosis. This enforces a routine depth limit of 150 to 180 fsw in general practice. Well-acclimated divers occasionally extend this limit to about 250 fsw, depending on individual competence. This procedure often works, but it is also often a recurring source of accident statistics.

b. Oxygen

With air as the gas source, oxygen will never be in short supply. It may however be added to reduce decompression time. Oxygen toxicity, however, can limit certain types of air diving, where the exposure is long and deep enough. However, nitrogen narcosis and decompression problems predominate in air diving. This is considered in more detail in relation to excursions from saturation.

c. Carbon dioxide

Carbon dioxide accumulation should occur rarely in air diving because of the availability of a large volume of gas. It does, however, become a factor in some kinds of equipment during exercise, and when SCUBA divers consciously control their breathing rate to conserve air. An increase in CO_2 can intensify nitrogen narcosis and susceptibility to oxygen toxicity.

d. Contaminants

This topic may be subdivided according to the source of the air being breathed. The ultimate source is of course the atmosphere, but the method of acquisition and compression has a great deal to do with the quality of the end product. There are two general methods: 1) a low-pressure compressor, with a reservoir, with the compressor running while the diver is at work; and 2) high-pressure compressed air supplied from tanks, carried by the diver (SCUBA) or through a hose. (Another source of compressed air is from gas suppliers; in this case air may be a nitrogen-oxygen mixture made up cryogenically. It is very unlikely to contain contaminants, but it will lack trace gases and may have an oxygen percentage ranging from 19 to 23%).

Although the equipment varies, the problems are about the same with both low- and high-pressure compressors. The greatest hazard is the intake of carbon monoxide, or less commonly by its generation in an overheated compressor. Catalytic filtration systems are available which effectively remove CO. These are considered too expensive for use with low-pressure compressors because of the very high volume flow and consequent need for frequent catalyst replacement. Ordinary filters do not remove carbon monoxide. In air diving the major difficulties with CO seem to be education and training of operators and crews to assure that compressor intakes are located so as to avoid drawing in CO, and ensuring that compressors deliver the right amount of gas and that they are properly maintained

Oil mist is another problem with air compressors. This mist is easily removed by relatively inexpensive filters, but when it is not removed it causes nausea and lung problems. Perhaps as important as the toxic effects of oil mist are its fire and explosion potential, significant around high pressure air, but especially dangerous where oil is allowed to contaminate equipment subsequently used in oxygen service.

As with CO, the main problem with oil is not lack of knowledge, but lack of distribution of available information—education and training.

2. Mixed-Gas Diving

a. Oxygen

Oxygen is overwhelmingly and without question the most significant element of mixed-gas diving. As mentioned elsewhere, oxygen presents a three-fold problem because of the necessity to avoid both too high and too low an oxygen concentration, and the equally important but different problem of fire safety.

Selection of the oxygen partial pressure to be used in each mode of diving depends on the duration of exposure and the conditions of the dive, as well as on other physical problems such as logistics, equipment, and fire safety. "Lockout gas" is usually adjusted to give the diver between 0.2 and 1.6 ATA of oxygen while he is working in the sea. The requirement here is for a partial pressure of oxygen as high as possible to minimize decompression, but below toxic limits. The selection of the proper gas mixture is necessarily a function of the depth at which the gas is used.

During decompression, oxygen is usually kept as high as is tolerable, but this may have to be quite a low concentration if the decompression is long. Typically oxygen averages about 0.5-0.7 ATA over a long decompression, a level which reflects a trade-off between logistics, decompression, and toxicity. Obtaining the proper mixture is a substantial problem of oxygen management in deep diving. Some diving companies order pre-mixed gases, store them in fairly large quantities on board the vessel, and recheck the analysis before use. Other companies maintain mixing and compression capabilities with each diving system. Training is a major current problem in this situation. The concepts of partial pressure, gas physics, and gas physiology are generally beyond the capabilities of the average diver, and current contracting practice may not permit a specialist in the crew. In addition to the obvious need for training, there is also a need for more and better instrumentation and automated gas handling equipment. As diving depths increase, these requirements are proportionately magnified.

b. Carbon Dioxide

Carbon dioxide does not play much of a role in operational planning but there is evidence that it should. Numerous incidents are recorded in which a diver, for one reason or another, attempted to overbreathe his breathing equipment. Such a condition can ensue when a diver exercises beyond a reasonable level or when the gas density of his breathing mixture is excessive for his mask or helmet. In the cases at point, divers have struggled back to the bell suffering from severe dyspnea, dizziness, and in some cases unconsciousness. The cause of this problem, referred to in the field as hyperventilation but more properly called overbreathing, is not known. It resembles laboratory situations in which carbon dioxide is allowed to build up well beyond the normal physiological range, and this suggests that CO_2 buildup is the physiological entity implicated in the diving situation. It is very probable that this mechanism is involved in many diving fatalities not otherwise explained; it is distressing that a problem so critical remains unexplained and almost unexplored.

c. Helium

Helium is the obvious gas for use as an inert diluent in deep diving because of its lack of narcotic properties, easy breathability, and relatively low cost. It is not without faults, however, since it has a destructive effect on the quality of the human voice, removes too much heat from the body both in a habitat or in the breathing gas, and has been implicated in the High Pressure Nervous Syndrome.

Although it is not considered a critical resource at this time, the supply of helium is not inexhaustible; once released into the atmosphere, it eventually leaves the earth's gravitational field. At the present time only a small part of the helium used in diving is recycled. The development and use of helium reclamation and recycling equipment is encouraged.

d. Trimix

For practical reasons most helium-oxygen diving mixtures actually contain small percentages of nitrogen. This improves the voice and thermal properties of the breathing mixture and reduces its cost; the effect of a nitrogen admixture on decompression is truly unknown at this point; different hypotheses claim it is both helpful and detrimental. Using air as a source of nitrogen in a trimix makes very good sense, but at the same time complicates the situation by requiring better training and instrumentation before it can be incorporated safely.

e. Contaminants

Trace contaminants are not a common problem in mixed-gas diving. Bottled or bulk compressed gases received from most suppliers are unlikely to contain any contaminants, partly due to the method of manufacture, but also because other users of these gases have much more rigorous requirements than those of the diving industry. Contaminants can, however, be added to gas mixtures during the mixing procedure, in transfer, and in storage. Hoses and transfer equipment should be purged before use.

Otherwise, however, pure gases have caused many fatalities, due either to mislabeling or misuse of properly labeled gas. This problem will never be fully solved, but improvements can be made by encouraging simple and convenient instrumentation, tight supervisory control by management, and, as in most other areas, better training.

3. Saturation and Excursion Diving

The work environment for a saturation dive is essentially the same as that for a standard mixed-gas short duration dive, and involves the same physiological problems and limitations. The special problems of saturation diving derive from the fact that the diver is living in a closed, artificial environment.

a. Oxygen

As usual, oxygen causes the major problems. For saturation diving, the habitat must be kept at a much lower oxygen level than is normally used by the lockout diver, because the saturation exposure is very long. Most operators maintain between 0.2 and 0.3 ATA of oxygen in the habitat. Some sort of oxygen analysis is always used, but continuous recording of the oxygen level is not common. Oxygen may be raised to 0.5-0.6 ATA during decompression.

One very dangerous aspect of the saturation environment is the fact that the oxygen concentration may be quite low, since it is the partial pressure that exerts the physiological effect. When such a mixture, which may be, for example, 1.5% at 1000 fsw, is reduced to lower pressure, as it might be during an aborted dive or lock transfer, it becomes totally inadequate for maintaining metabolic requirements. There have been accidents as a result of this phenomenon.

b. Carbon dioxide

Carbon dioxide is normally removed from the saturation diving habitat by means of sodasorb or baralime scrubbers. These may be located inside the chamber or in an external loop. If these are inside the chamber, rather heroic methods, such as pneumatic and hydraulic motors and magnetic drives, are sometimes required to avoid the use of electricity, because of the fire risk.

Some operators run their scrubbers continuously, others turn them on only when CO_2 reaches some set upper limit (3-11 mm of mercury, typically). Responsible operators monitor the CO_2 level either with infra-red analyzers or the simpler analysis tubes. In a properly maintained system excess CO_2 is not a problem, but when there is a scrubber failure it can cause a life-threatening situation.

c. Water vapor

The removal of water vapor from a saturation habitat presents a substantial engineering and mechanical challenge to the operator. Dehumidification is normally done by passing the chamber atmosphere over a cold coil to condense out the moisture, followed by reheating. It is perfectly acceptable to locate the coil inside the chamber, as long as thermal control is maintained. Another method of water removal is by means of chemical absorbents such as silica gel or a molecular sieve.

The maintenance of liveable relative humidity (below 70%) is more than a comfort factor; major diving operations have been halted by an outbreak of swimmer's ear, a malady which is much easier to control if chamber humidity can be kept low.

d. Inert gas

Virtually all commercial saturation diving is conducted with helium. The reason for this is that operations in water shallower than the helium range can readily be conducted with surface diving. The range between 150 and perhaps 250 fsw has been shown to be accessible by means of nitrogen saturation procedures, but these have not yet been developed for commercial use.

Long-term effects of living in a helium environment have been studied, and our present state of knowledge suggests that these do not appear to be limiting problems. Temperature must be maintained at a much higher than normal level (about 86-90 °F or 28-30 °C). Electronic helium voice unscramblers are frequently used, and at depths greater than 300 fsw are handy if not essential. Divers do learn to speak more intelligibly after being in helium for a few days and their listeners also learn to understand better. Whether or not unscrambling is used, high-quality communication equipment is important.

The use of helium poses substantial engineering problems. It tends to leak out of anything it is kept in, and into anything placed within it. Television tubes are quickly destroyed when exposed to the hyperbaric helium environment. Helium is difficult to circulate with ordinary blowers, and its thermal properties may disable certain equipment. One very nice thing about the saturation habitat is that it will not support combustion, and though fire-safe equipment needs to be used and fire safety procedures need to be followed this is not critical during the bottom phases of saturation operation. It is probably important, when a helium saturation decompression profile is to be used, to keep excess nitrogen from building up in the environment, although some saturation methods call for a switch to air near the surface.

e. Contaminants

The saturation environment is one place where minor contaminants play an important role in diving. Most operators use either activated charcoal or activated alumina to remove heavy organic contaminants and odors. These are effective when operating properly, but a chamber environment can become terribly foul when odor control is not available. Normal body-generated contaminants usually do not impose operational limits or cause injury in present-day short saturation exposures, but they must be controlled in long exposures.

Carbon monoxide is a particular problem because it is not removed by any of the standard scrubbing techniques. With reasonable care carbon monoxide can be kept out of the saturation atmosphere. It can and must be monitored with inexpensive detector tubes.

Other contaminants have from time to time caused problems, some of them serious, in saturation experiences. It is not feasible to provide extensive analytical capability offshore; most operators rely on smell or physiological response to detect problems. Greater knowledge of what to expect and what to look for could improve safety in this area.

III. PROBLEMS TO BE SOLVED

A. General

Uncertainty about the long-term effects of diving currently overshadows diving operations. The high incidence of asceptic bone necrosis, found in Japanese and German studies to be as high as 50% of the diving population, is the basis of such concern. Lack of knowledge of the long-term effects of diving affects the setting of diving standards, produces legal problems, and adds a moral dimension to the scheduling of certain diving operations. It will take quite a long time to determine long-term effects. Short of this, it is necessary to get on with short-term approaches to this problem and to carry out careful epidemiological studies on long-term diving effects.

The establishment of adaptive capacity and tolerance criteria for divers is the first important step in protecting divers and providing diving companies with better information for diving schedules. To set up such criteria it is necessary to develop an integrative approach which simultaneously correlates physiological and biochemical data at rest, during exercise, and under pressure, with psychological evaluations and performance tests. For example, it has been shown that a single dive to 180 fsw has only a small affect on blood and urine parameters. The observed changes return to normal within two days of surfacing. However, when the dives are repeated at intervals of 2 days, the response is greater and of longer duration. It has been difficult in the past to establish a consensus on behavioral effects or standards of measurement for behavioral changes. Progress in this area is very much needed. However, more emphasis should perhaps be given to the simple psychological evaluation of symptoms, such as fatigue and other complaints, because such a catalog of symptoms could be used in the field as indications of limits. The following three criteria should be established: 1) The upper limits for air or helium-oxygen for a particular diving mode; 2) The time intervals for repetitive diving carrying out the same operations; 3) Recovery periods necessary for return to normal following each type of diving operation.

It is known that great individual differences exist in the capacity to adapt to diving. It would therefore be desirable to develop individual response profiles for all divers.

The need to study individual responses to environmental stress has been emphasized only in recent years. As one example, it has been shown that temperature regulation consists not only of physiological temperature regulation, but also of behavioral temperature regulation, which shows great individual differences.

The attempt has been made to measure accumulating oxygen based on the time during which divers are exposed to increased oxygen levels. This approach merits extension to the study of accumulating diving loads where the effects of exposures to increased pressure per se are correlated with the effects of oxygen, nitrogen, and other gases.

B. Oxygen

The topic of oxygen is being addressed by committee #10. However, certain aspects of oxygen are so important to any discussion of diving that they need to be mentioned here. Many accidents have happened and are continuing to happen as a result of divers breathing gases which contain an inadequate amount of oxygen. To counteract this problem directly, better monitoring and control equipment should be made available, and divers and dive crews should be better trained in the importance of good oxygen management. Equipment which would cheaply, easily, and safely remove oxygen from an inert gas atmosphere would be a boon to diving.

The matter of fire and oxygen safety, though covered by another committee, is too important to ignore. Divers are still dying in chamber fires and topside workers are still being injured by oxygen explosions and fires in piping and equipment. Proper materials and equipment for chamber safety, fire extinguishing and fire detection capabilities, and the development of improved procedures all merit further research. Proper procedures for oxygen safety need to be disseminated.

The upper and lower limits for oxygen in saturation air diving should be established. Recent studies have shown that during oxygen/nitrogen diving to 198 fsw, a "Chouteau" effect was observed during the beginning of the dive when the oxygen tension was 0.2 ATA. Divers complained about nausea and great fatigue within 3 hours after the beginning of the dive and after reaching the 198-fsw depth. When the oxygen concentration was changed to 0.3 ATA, the symptoms disappeared rapidly. On the other hand, the upper limit of the oxygen level producing oxygen toxicity has to be re-evaluated for saturation air diving conditions.

C. Carbon Dioxide

At the present time it is not clear what the lasting effects of chronic hypercapnia are at normal atmopheric pressure. It had been predicted that safe levels of CO_2 would be between 0.5 to 0.8% CO_2 (18). Recent studies have shown that prolonged exposure to 0.85 and 1.0% CO_2 results in significant alteration of calcium-phosphorus metabolism (11). British studies have demonstrated the effects of prolonged exposure to 0.5% CO_2 on calcium-phosphorus urinary excretion patterns (5). These hypercapnia or calcium-phosphorus metabolism effects produced by exposure to low levels of phosphorus metabolism effects produced by exposure to low levels of CO_2 seem to be closely linked with an acid-base balance regulation involving slow-acting bone buffering, primarily. In contrast, acid balance regulation during exposure to higher CO_2 concentrations (3% and above) is accomplished predominantly by fast-acting renal mechanisms (14). The threshold limit value of ambient CO_2 for continuous 90-day exposure is set at 0.5% CO_2 and represents an upper limit; it should probably be reduced to 0.3% CO_2.

For a real understanding of the long-term effects of chronic hypercapnia both under atmospheric pressure and increased pressure, longitudinal animal studies are urgently needed. Particular emphasis should be placed on the effects of CO_2 on lungs, kidneys, and bone development, and the function and contribution of these organs to the regulation of an acid-base balance.

Carbon dioxide retention plays an important role in relation to the resistance provided by respiratory equipment as well as to increased gas density under increased pressure. Retention is particularly important as a limiting factor in exercise in diving conditions or during exposure to increased pressure. Its role requires further study. Both CO_2 and nitrogen have narcotic properties and the interaction of the two needs to be clarified.

Occasionally something goes wrong with a diver's environment, or he is exposed unavoidably to an environmental stress (e.g., cold). It is essential to know what to do, when it is important to hurry, or when haste is counterproductive. A recent fatal accident seems to have been the result of overzealous action on the part of a chamber operator to correct a condition that in itself may not have been nearly so tragic.

Research needs to be done to increase our knowledge of short-term limits, and available knowledge needs to be transmitted.

D. Inert Gases

1. Nitrogen

In a practical sense nitrogen narcosis can be eliminated simply by not using nitrogen deeper than 150 fsw, but if methods could be found to alleviate the narcosis it might be possible to dive to much greater depths breathing air or a mixture. Then too, the fact that nitrogen can counteract HPNS suggests some commonality of mechanism. Basic research on how inert gases induce narcosis may elucidate problems other than just inert gas narcosis. An understanding of the mechanisms of narcosis will also provide answers about the mechanism of anesthesia, for example.

Saturation air diving is in its infancy and little research has been carried out at 100 fsw or deeper. There is reason to believe that adaptation may permit man to breathe compressed air at narcotic depths without debilitating narcosis, provided only that sufficient time is spent at depth. The times required at different depths for adaptation to occur and wear off are not known, and a systematic research program to determine this data is required. Nor is there sufficient data on individual adaptation to daily dives on compressed air. How many days are required to adapt? What is the amount of adaptation each day? What is the individual variation? How quickly does the adaptation wear off?

Quantitative data on the effects of such synergistic factors as temperature, carbon dioxide, work levels, and duration of exposure are at present poorly defined and extensive research is required to define the limitations and interactions of such factors.

Much of the lack of sound quantitative data on the effect of narcosis on divers is due to the difficulty in measurement. Various psychological and performance tests have been used, but there is a considerable need to find, select, and use standardized tests administered in a standard manner so that a reliable body of knowledge can be accumulated.*

Further information on the neurophysiological changes caused by increased pressures of nitrogen is required to develop a physiological test of narcosis. Cortical-evoked potentials of the electroencephalogram (EEG) have received study, as has the frequency analysis of the EEG. However, both these methods have not proved entirely satisfactory. Recent work implying that saturation with nitrogen at a given depth will permit excursions to a greater depth without narcosis needs verification and extension. If this proves to be correct, an avenue for more extensive use of air will have been opened.

Pharmacological prevention of narcosis has been studied to date only in animals. However, this work suggests that some compounds may well be capable of narcosis prevention. Whether or not divers would wish to take such a compound routinely can be debated, but there may be emergency or accidental situations in which this could be useful. Even more important is that using pharmacological agents as tools is helpful in determining the mechanisms of anesthesia or narcosis.

As with so many contemporary diving problems, the solution to the narcosis problem can only be found when its etiology is better understood. This requires a considerable body of research on the interaction of cell membranes with nitrogen, helium, and other inert gases or anesthetics, and an understanding of how this interaction affects neurophysiological mechanisms in the axon and synapse to produce narcosis and anesthesia.

2. Neon, Hydrogen, and Other Inert Gases

Alternatives to the use of helium and nitrogen exist, and research on these should continue.

---

*This question was addressed at the 4th Undersea Medical Society Workshop, "The Development of Standardized Assessment of Underwater Performance", October 1973 (Report No. WS 3-20-75) and will be considered by the committee on Cognitive and Psychomotor Performance.

3. Helium

Work must continue on the physiological effect of long-term exposure to hyperbaric helium environments. It needs to continue in the area of communications, (helium speech unscrambling) and thermal control. Less well known physiological effects may be too important to be ignored and their long-term effects must also be studied.

Of major interest is the conservation of helium, which is related to several problems. One of these problems is the use of rebreathers of various sorts to conserve helium. Closed-circuit and semi-closed circuit breathing equipment is potentially dangerous at its present stage of development; in its present state it does not have the confidence of divers. However, its eventual use is inevitable, and work needs to be done to provide proper monitoring, alarm, and training capabilities. A push-pull system from the bell to the diver and back to the bell, with the bell's conditioning system rejuvenating the gas, has been needed for a long time, but at the present time no suitable system is on the market. When such systems are developed they must be tested and evaluated to make sure they are safe.

There are many possibilities for other methods of reclaiming and reusing helium. These can be extremely simple or quite complex, and they need to be evaluated; procedures also need to be worked out to assure proper application of this technology. Research on conservation of helium is merited.

4. Physiological Detection

It is important to expand our knowledge of how to use physiological responses as a monitoring system. For example, increased carbon dioxide retention causes an increase in ventilation, and perhaps headaches and other responses, depending on the level and rate of change. The presence of high levels of oxygen can be detected by timing the period to "grey out" when retinal vessels are occluded. The presence of helium in a breathing mixture is easily detected by speech changes. Since diving operations will continue to be carried out with minimal instrumentation, it is imperative that a systematic catalog of responses be developed to enable operators to use the exquisitely sensitive human body to help maintain a proper working environment. This requires both laboratory research and training.

5. Toxicity of Hyperbaric Contaminants

Environmental control of most toxic substances has occurred as a reactive process. A man becomes ill or is killed while working in a particular environment, the toxic substance(s) is identified, its toxic effects quantitated, and threshold limit concentrations are set. Then, hopefully, further debilitating or fatal exposures are avoided.

A more proper goal, of course, is both to control known toxic agents and to identify new problems without a casualty to spur us to action. To accomplish this goal for hyperbaric environments, for which dismally few toxicity studies of individual contaminants or of these complex atmospheres have been completed, is extraordinarily complicated. Acute hyperbaric toxicity studies are much easier to do than chronic studies, and the equipment required is much simpler. However, while the acute studies are important for setting short-term emergency exposure limits, they are severely limited in value in establishing working limits for situations in which divers are exposed to contaminants at low levels every day they work. There is a pressing need for the development of techniques, equipment, and facilities to investigate the chronic hyperbaric toxicity of these contaminants and mixtures of these contaminants.

Possible interactions between toxicity and various environmental stresses, and of the toxicity of complex atmospheres, also require careful attention. The number of experiments required to assess interactions in complex environments can become very large. However, because of the much simpler physical requirements for studying toxicity at one atmosphere and the availability of normobaric toxicological facilities, many of these investigations could be performed in normobaric chambers. As unusually toxic materials or toxic combinations of substances are identified they can then be studied at pressure.

Many of these hyperbaric toxicity problems which presently seem of little more than esoteric interest will become urgent when divers are required to spend longer times in deep-sea habitats in contact with low levels of a variety of potentially toxic contaminants. Careful chemical analysis of habitat atmospheres during the development of closed deep-sea environments will be useful in limiting the introduction of dangerous, gaseous contaminants. Yet it is clear that exposure to materials which have relatively minor acute toxic effects can also produce grave chronic consequences. The classic examples of this are the various chemical carcinogens which have now been recognized. The effects of hyperbaria on these subtle chronic changes are unknown. The development of adequate facilities to undertake studies of hyperbaric toxicology will serve at least three purposes: 1) providing data to reassure the diver and design engineers that the environments are indeed safe; 2) weeding out hazardous materials; 3) finally, when occasions arise where it is necessary to study a material that has proved toxic, a facility where this can be accomplished will be available.

IV. FUTURE REQUIREMENTS

Diving in the next ten years will increase in both depth and duration. Problems of a character substantially different from those covered in this report are not expected. However, an increase in the intensity of most of the problems covered here is inevitable, and will probably be in proportion to depth and duration. Programs and priorities proposed here have been prepared with this in mind.

V. PRIORITIES

A. Short-term Priorities

1. Education and Training of Diving Personnel

    a. Normal and emergency environmental limits

    b. Training in physiological aspects of equipment (diving apparatus, control and monitoring equipment.)

    c. Training in recognition of physiological warning signs.

2. Evaluation, Testing, and Improvement of Equipment

    a. Breathing apparatus (including rebreathers) for both chamber and submersible diving.

    b. Environmental control and monitoring systems.

    c. Reclamation apparatus for gases, including O_2 and CO_2.

3. Improved Information Exchange

    a. Better accident and incident analysis and reporting.

    b. Epidemiological studies of divers should be initiated as early as possible.

4. Research to Establish Limits

    a. Time intervals and recovery periods for different diving modes.

    b. Research on physiological warning signs.

    c. Interaction of physiological gases under increased pressure with each other and trace contaminants.

    d. Research on the use of air and N_2-O_2 diving to greater depth.

B. Long-term Priorities

Long-term effects of extended exposure to increased O_2, CO_2, N_2, and trace contaminants.

VI. RESEARCH FACILITIES

Research facilities for pressure research with human subjects and special high-pressure animal chambers have been listed.

However, it should be pointed out that a number of areas within the scope of this committee do not require such big facilities or do so only at some point of the research program. The larger pressure research facility could serve as a Regional Center where investigators from surrounding universities could come to complete research projects.

The designation of laboratories to undertake investigations of hyperbaric toxicology is extremely difficult. Chronic hyperbaric toxicity studies, involving large numbers of animals and long-term exposures (from 90 days to the life of the animal), require an expensive, complex hyperbaric facility. Few installations are equipped to do this work. However, acute hyperbaric toxicity studies require only one chamber, and a great amount of required toxicity data relating to the diving environment could be obtained in normobaric inhalation chambers. Competent investigators who do not have access to large hyperbaric facilities should therefore not be excluded from consideration.

LABORATORIES WORKING IN HIGH PRESSURE PHYSIOLOGY

Civilian Laboratories

1. F. G. Hall Environmental Laboratory, Duke University Medical Center, Durham, North Carolina
   1000 fsw, saturation, 6 divers, wet, altitude, 6 interlocking chambers; 4500 fsw animal (dog); full laboratory capability.

   Peter B. Bennett

2. Institute for Environmental Medicine, University of Pennsylvania, Philadelphia, Pennsylvania
   1800 fsw, saturation, 4 divers, wet, altitude, 4 interlocking chambers; 4500 fsw animal (monkey); USN-certified; full laboratory capability.

   C. J. Lambertsen

3. Marine Biomedical Institute, University of Texas Medical Branch, Galveston, Texas
   800 fsw, saturation, wet, 4 divers

   Brian A. Hills

4. Tarrytown Labs, Ltd., Tarrytown, New York
   1000 fsw, dry only, saturation to 675 fsw, 2 divers, altitude, small animals to 5000 fsw.

   Robert W. Hamilton, Jr.

5. S.U.N.Y. at Buffalo, New York
   5000 fsw, wet, 3 divers, altitude

   Herman Rahn

6. Virginia Mason Research Center, Seattle, Washington
   1500 fsw, saturation, 2 divers; 400 fsw, animal (large); 1800 fsw, animal (small); full laboratory capability.

   Kent H. Smith

7. Beth Israel Medical Center, New York, New York
Shallow, small animal, chambers, altitude

Chryssanthos P. Chryssanthou

8. Bowman-Gray Medical School, Wake Forest University, Winston-Salem, North Carolina
Small animal

James G. McCormick

9. Colorado State University, Fort Collins, Colorado
250 fsw, 10 divers, large animals, altitude

Peter Hall

10. Institute for Applied Physiology and Medicine, Seattle, Washington
300 fsw, 2 divers

Merrill C. Spencer

11. St. Lukes Hospital, Milwaukee, Wisconsin
225 fsw, 8 divers

Eric P. Kindwall

12. Texas A&M University, College Station, Texas
600 fsw, large animals

William P. Fife

13. University of Hawaii, Honolulu, Hawaii
Aegir mobile habitat, 600 fsw, DDC on shore

David Yount

14. University of Rochester, Rochester, New York
Animal chamber

A. T. K. Cockett

15. Harbor Branch Foundation, Fort Pierce, Florida
2 lockout submersibles, 1500 fsw, 1000 fsw DDC, saturation, on *R. V. Johnson*

16. University of North Dakota, Grand Forks, North Dakota
Extensive animal chamber complex

Thomas Akers

17. University of Southern California at Avalon, California
225 fsw, 4 divers

Andrew J. Pilmanis

18. Westinghouse Ocean Research and Engineering Center, Annapolis, Maryland
1500 fsw, wet, saturation, 3 divers

19. Wrightsville Marine Biomedical Laboratories, Wilmington, North Carolina
600 fsw animal (large); 3200 fsw, animal (gill breathers)

Ralph W. Brauer

Military Laboratories

1. Naval Coastal Systems Laboratory/Naval Experimental Diving Unit, Panama City, Florida
2500 fsw, saturation, wet, large staff; full laboratory capability

W. H. Spaur

2. Naval Medical Research Institute, Bethesda, Maryland
3300 fsw, saturation to 2200, wet 2200 (due 1978), altitude, full laboratory capability

Large staff

3. Naval Submarine Medical Research Laboratory, Groton, Connecticut
300 fsw, 3 divers, dry; full laboratory capability

Claude Harvey

4. USAF School of Aerospace Medicine, Brooks Air Force Base, San Antonio, Texas
200 fsw, 4 divers, 2 chambers, altitude

Jefferson C. Davis

5. U. S. Navy Submarine Development Group One, San Diego, California
Mark I Deep Diving System (1000 fsw DDC) on MV ELK RIVER

Paul Linaweaver

6. Naval Biomedical Research Laboratory, Oakland, California
600 psi, animal, physiological and aerobiological studies

Andre B. Cobet

LABORATORIES WORKING IN HIGH PRESSURE TOXICOLOGY

1. Toxicology Division, Environmental Biosciences Dept., Naval Medical Research Institute, Bethesda, Maryland
Single chamber, 1500 psi, 1975.

CDR. L. J. Jenkins, Jr., MSC, USN

2. Animal Toxicology Unit, Environmental Health Effects Laboratory, Naval Medical Research Institute, Bethesda, Maryland
Chamber complex of animal chambers for 90-day or life-time studies, 3000 psi (due 1978)

3. University of North Dakota, Grand Forks, North Dakota
Extensive animal chamber complex

Thomas Akers

REFERENCES

1. Bennett, P. B. 1966. The Aetiology of Compressed Air Intoxication and Inert Gas Narcosis. Oxford: Pergamon Press.
2. Bennett, P. B. 1975. Inert gas narcosis. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. H. Elliott. London: Bailliere Tindall, p. 207-230.
3. Bradley, M. E., Ed. 1974. Sealab. In: Respiratory Limitations of Underwater Breathing Equipment. Report of the 2nd Undersea Med. Soc. Workshop. WS:4-15-74, p. 1.
4. Case, E. M., and J. B. S. Haldane. 1941. Human physiology under high pressure. I. Effects of nitrogen, carbon dioxide and cold. J. Hyg. 41:225-249.
5. Davies, D. M. 1972. The effects of extended hypercapnia. Pro. Roy. Soc. Med. 65:796-797.
6. Eisele, J. H., I. I. Eieger and M. Muallem. 1967. Narcotic properties of carbon dioxide in the dog. Anesthesiology 28:856.
7. Fagraeus, L. and D. Linnarson. 1973. Maximal voluntary and exercise ventilation at high ambient pressures. Foervarsmedicin 9:275-278.
8. Fagraeus, L., and C. M. Hesser. 1970. Ventilatory response to CO_2 in hyperbaric environments. Acta Physiol. Scand. 80:19A-20A.
9. Hesser, C. M., and J. Adolfson, and L. Fagraeus. 1971. Role of CO_2 in compressed air narcosis. Aerospace Med. 42:163-168.
10. McAleavy, J. C., W. L. Way, A. H. Allstate, N. P. Guadagni, and J. W. Severinghaus. 1961. The effect of P_{CO_2} on the depth of anaesthesia. Anesthesiology. 22:260.
11. Messier, A. A., E. Heyder, W. R. Braithwaite, C. Mc Cluggage, A. Peck, and K. E. Schaefer. 1975. Calcium, magnesium and phosphorus metabolism and parathyroid calcitonin function during prolonged exposure to elevated CO_2 concentrations on submarines. Nav. Submar. Res. Lab. Rept. No. 802, 1975.
12. Proctor, L. D., C. R. Carey, R. M. Lee, K. E. Schaefer, and H. van den Ende. 1972. Electroncephalographic changes during saturation excursion dives to a simulated sea water depth of 1000 feet. Aerospace Med. 43:867-877.
13. Rose, C. S., R. A. Jones, L. J. Jenkins, and J. Siegel. 1970. The acute hyperbaric toxicity of carbon monoxide. Toxicol. Appl. Pharmacol. 17:752-760.
14. Schaefer, K. E. 1975a. CO_2 effects under conditions of raised environmental pressure. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. H. Elliott. London: Bailliere Tindall.
15. Schaefer, K. E. 1975b. Physiological stresses related to hypercapnia during patrols on submarines. Nav. Submar. Med. Res. Lab. Report No. 799, 1975.
16. Schaefer, K. E. 1965a. Adaptation of circulation to life under increased pressure. In: Handbook of Physiology. Circulation. Washington, D. C.: Am. Physiol. Soc., sect. 2, vol. III, chapt. 51, p. 1843-1873.

17. Schaefer, K. E. 1965b. Adaptation to breath-hold diving. In: *Physiology of Breath-hold Diving and the Ama of Japan*. Washington, D. C.: Natl. Acad. Sci., Publication 1314, p. 237-251.

18. Schaefer, K. E. 1961. Concept of triple tolerance limits based on chronic carbon dioxide toxicity shares. *Aerospace Med.* 32:197-204.

19. Severinghaus, J. W. 1974. Carbon dioxide transport. *Carbon Dioxide and Metabolic Regulations*. p. 138-143.

20. U.S. Navy. 1973. *Proc. Diver's Gas Purity Symp.* Report No. 2-73. Sponsored by U.S. Navy Supervisor of Diving, Naval Ship Systems Command, Battelle, Columbus, Nov. 27-28, 1973.

21. Wright, Brandon. 1974. Physiological testing of an air and helium hard hat system and a closed-circuit underwater breathing apparatus. *Respiratory Limitations of Underwater Breathing Equipment*. 2nd Undersea Med. Soc. Workshop, Rept. No. WS:4-15-74.

OXYGEN

Part #10 of the

National Plan for the Safety and Health of Divers in their Quest for Subsea Energy

Produced by:

James M. Clark, M.D., Ph.D. (Chairman)
Assistant Director
Institute for Environmental Medicine
University of Pennsylvania
Philadelphia, Pennsylvania

Morris D. Faiman, Ph.D.
Department of Pharmacology and Toxicology
School of Pharmacy
University of Kansas
Lawrence, Kansas

Aron B. Fisher, M.D.
Department of Physiology
School of Medicine
University of Pennsylvania
Philadelphia, Pennsylvania

Aaron P. Sanders, Ph.D.
Professor and Director
Division of Radiobiology
Duke University Medical Center
Durham, North Carolina

Donald F. Tierney, M.D.
Division of Pulmonary Disease
University of California
Los Angeles, California

TABLE OF CONTENTS and Organization for part 10

Oxygen

I. INTRODUCTION 1

II. SUMMARY OF KNOWN INFORMATION 1

A. Physiologic Effects of Oxygen

1. Effects on Arterial Blood Oxygen Content

2. Effects on Carbon Dioxide Transport

3. Cardiovascular Effects

4. Effects on Control of Ventilation

5. Exercise Effects

6. Effects on Red Blood Cell Formation

7. Effects on Biological Oxidations

8. Displacement of Inert Gas

B. Toxic Effects of Oxygen

1. Effects of Continuous Exposure to Toxic Oxygen Pressures

2. Effects of Repeated Exposures to Toxic Oxygen Pressures

3. Mechanisms of Oxygen Toxicity

4. Factors Which Modify Rate of Development of Oxygen Poisoning

5. Sensitivity to Oxygen Toxicity

III. RECOMMENDATIONS 5

A. Mechanisms of Oxygen Toxicity

B. Effects on Organ Systems and Functions

C. Modifying Factors

D. Sensitivity

E. Oxygen Therapy in Diving Accidents

IV. FACILITIES AND PERSONNEL.. 9

I. INTRODUCTION

The use of oxygen at increased pressures can enhance the safety and efficiency of diving and decompression operations. However, excessive exposure may cause serious injury or death from neurologic or lung damage. The objectives of safe and efficient diving are to utilize the advantages afforded by oxygen while avoiding its toxic effects.

Oxygen is used in diving operations to decrease the uptake and hasten the elimination from the body of dissolved gases, such as nitrogen or helium. Since decompression from great depths can require up to a week or longer, optimal use of oxygen can significantly shorten dive duration. Concurrently, prolonged exposure to increased oxygen pressures increases the risk of serious toxic effects. The extreme ambient pressure at great depths creates an additional hazard because the range of inspired oxygen concentration must be very narrow; for example, at 1600 fsw, the safe range is about 0.4% to 1.0%. For this reason, controlling the composition of the breathing gas precisely is imperative at such depths; the risk of oxygen toxicity or severe oxygen lack is a constant hazard.

Increased oxygen pressures are used effectively in the treatment of decompression sickness* and air embolism. The goal of this therapy is to optimize the desirable effects of oxygen, such as improved oxygenation of ischemic (oxygen-deficient) tissues and relief of circulatory obstruction caused by gas bubbles, while minimizing the concurrent development of toxic effects. It is important to recognize that greater understanding of both the therapeutic and toxic properties of oxygen will increase its effectiveness not only in the treatment of diving accidents, but also in all other forms of oxygen therapy.

II. SUMMARY OF KNOWN INFORMATION

This summary is not a comprehensive review of the vast literature on the physiologic and toxic effects of oxygen. We have not cited the contradictory evidence when a point seemed to be reasonably established. For specific papers, the reader is directed to the several excellent reviews which are listed in the references.

It is not always possible to distinguish clearly between the physiologic and toxic effects of oxygen. We have developed a working definition which achieves this in most cases. Physiologic effects are defined as those which are not inherently detrimental, do not cause progressive damage during continuous exposure, and leave no residual effects. In contrast, toxic effects cause progressive cellular damage during continued exposure and may have residual effects.

---

*Report 2T discusses decompression sickness in greater detail.

A. Physiologic Effects of Oxygen

1. Effects on Arterial Blood Oxygen Content

Elevation of the inspired oxygen pressure increases the blood arterial oxygen pressure and content. These effects are responsible for both the desirable and dangerous effects of oxygen in diving. In a man breathing air at sea level, one liter of arterial blood contains about 200 ml of oxygen. For each additional atmosphere of oxygen pressure, there is a 20-ml increment of oxygen dissolved in each liter of blood. Although this increases blood oxygen content by only 10% at sea level, it can provide most or all of the oxygen consumed by the tissues at higher ambient pressures.

2. Effects on Carbon Dioxide Transport

Part of the carbon dioxide produced by tissue metabolism is carried away bound to hemoglobin by venous blood. The carbon-dioxide-carrying capacity of hemoglobin is decreased by the presence of bound oxygen. At a high inspired oxygen pressure, the increased content of hemoglobin-bound oxygen in venous blood decreases the quantity of carbon dioxide combined with hemoglobin, and increases the quantity which must be carried in physical solution. Consequently, the quantity of carbon dioxide dissolved in the tissues can be increased, resulting in an increase in tissue acidity.

3. Cardiovascular Effects

Exposure to increased oxygen pressures causes vasoconstriction in at least some vascular beds, and reduces cardiac output and heart rate. Decreased tissue blood flow is a result of these combined effects and can slow the removal of dissolved gas from the tissues during decompression from high ambient pressures.

4. Effects on Control of Ventilation

Increased oxygen pressures have both depressant and stimulant effects on ventilation. The depressant influences are mediated by decreased activity of the peripheral chemoreceptors and perhaps by an additional effect on the respiratory control centers in the brain. The stimulant effects are caused by increased levels of carbon dioxide and acidity in these centers. The result of these concurrent effects is usually an abrupt decrease in ventilation, followed within seconds by a return to near-normal or increased levels.

5. Exercise Effects

The capacity for heavy exercise is extended by an increased arterial oxygen content. Exercise-induced increments in ventilation, heart rate, and lactic acid production are less during oxygen exposure than when breathing air. Such effects may be

I. INTRODUCTION

The use of oxygen at increased pressures can enhance the safety and efficiency of diving and decompression operations. However, excessive exposure may cause serious injury or death from neurologic or lung damage. The objectives of safe and efficient diving are to utilize the advantages afforded by oxygen while avoiding its toxic effects.

Oxygen is used in diving operations to decrease the uptake and hasten the elimination from the body of dissolved gases, such as nitrogen or helium. Since decompression from great depths can require up to a week or longer, optimal use of oxygen can significantly shorten dive duration. Concurrently, prolonged exposure to increased oxygen pressures increases the risk of serious toxic effects. The extreme ambient pressure at great depths creates an additional hazard because the range of inspired oxygen concentration must be very narrow; for example, at 1600 fsw, the safe range is about 0.4% to 1.0%. For this reason, controlling the composition of the breathing gas precisely is imperative at such depths; the risk of oxygen toxicity or severe oxygen lack is a constant hazard.

Increased oxygen pressures are used effectively in the treatment of decompression sickness* and air embolism. The goal of this therapy is to optimize the desirable effects of oxygen, such as improved oxygenation of ischemic (oxygen-deficient) tissues and relief of circulatory obstruction caused by gas bubbles, while minimizing the concurrent development of toxic effects. It is important to recognize that greater understanding of both the therapeutic and toxic properties of oxygen will increase its effectiveness not only in the treatment of diving accidents, but also in all other forms of oxygen therapy.

II. SUMMARY OF KNOWN INFORMATION

This summary is not a comprehensive review of the vast literature on the physiologic and toxic effects of oxygen. We have not cited the contradictory evidence when a point seemed to be reasonably established. For specific papers, the reader is directed to the several excellent reviews which are listed in the references.

It is not always possible to distinguish clearly between the physiologic and toxic effects of oxygen. We have developed a working definition which achieves this in most cases. Physiologic effects are defined as those which are not inherently detrimental, do not cause progressive damage during continuous exposure, and leave no residual effects. In contrast, toxic effects cause progressive cellular damage during continued exposure and may have residual effects.

---

*Report 2T discusses decompression sickness in greater detail.

desirable during the performance of underwater work.

6. Effects on Red Blood Cell Formation

Production and total mass of red blood cells are regulated in part by the circulating level of the hormone, erythropoietin. Increased oxygen pressures decrease the secretion of this hormone by the kidney, which is associated with a decrease in blood hemoglobin concentration. Following a multi-day exposure to high oxygen pressures, an abrupt transition to hypoxic (low oxygen) conditions could be detrimental.

7. Effects on Biological Oxidations

Molecular oxygen participates in many cellular biochemical reactions. Increased dissolved oxygen displaces the equilibrium of these reactions in the direction of increased concentration of oxidized products. Examples are oxidization of electron transport chain components, and increased production of peroxides and other reactive species.

8. Displacement of Inert Gas

Raising the oxygen percentage of inspired gas necessarily decreases the percentage of inert gas which constitutes the balance of the mixture. The resulting reduction of inert gas pressure in arterial blood provides an increased diffusion gradient for elimination of inert gas from body tissues. The importance of this effect in diving operations is that it can be used to shorten the duration of decompression.

B. Toxic Effects of Oxygen

The time required to produce oxygen poisoning decreases as oxygen pressure increases. Oxygen at high pressure affects basic functions common to all cells, but the sensitivity of different tissues varies widely. Thus, the manifestations of oxygen toxicity will vary depending upon oxygen pressure and duration of exposure. For example, lung damage limits the duration of oxygen exposure at about one ATA, while at pressures above two ATA, brain damage may appear first. The effects of oxygen poisoning appear to be completely reversible if the duration of exposure is not too long. Failure to stop a single exposure in time or repeated exposures with insufficient recovery intervals will cause residual effects.

1. Effects of Continuous Exposure to Toxic Oxygen Pressures

Oxygen exposure at a pressure of 0.6 ATA is known to produce biochemical, morphologic, and functional changes in the lung in animals and may decrease the ability of the lung to combat infection and increase the likelihood of pneumonia. At one ATA of oxygen, continued exposure causes fluid accumulation and hemorrhage in the lung, leading to severe impairment of oxygen transfer into the blood and ultimate death from oxygen lack in vital organs.

During exposure to higher oxygen pressures, neurologic manifestations of oxygen toxicity may develop, which include twitching of the small muscles in the face and hands, tremor, confusion, irritability, and convulsions. Residual neurologic deficits do not occur in animals or man following single exposures or widely spaced repeated exposures which are stopped at the onset of any symptom. Exposures which are continued past this point may cause permanent neurologic damage or death. Increased pressures of oxygen are also toxic to the eye; injury ranges from reversible impairment of peripheral vision to retinal damage with permanent blindness.

Oxygen is also toxic to other tissues such as the heart, kidney, gonads, liver, adrenal glands, and the blood-forming system. These effects are generally less well documented than those involving lungs and brain. Additional information about oxygen effects on these organs should be obtained to determine possible long-term effects on divers.

Prolonged exposures are necessarily limited to oxygen pressures lower than one ATA, because fatal lung or neurologic injury occurs at higher pressures. Animal experiments have shown that long-term exposures (weeks) to less than one ATA of oxygen can produce irreversible lung damage, with scarring and emphysema-like changes. Studies of chronic pulmonary oxygen poisoning are few, and long-term studies of oxygen effects on other tissues are few or non-existent.

2. Effects of Repeated Exposures to Toxic Oxygen Pressures

Repeated exposures to toxic oxygen levels can produce cumulative effects if sufficient time for recovery is not allowed between exposures. Preliminary evidence indicates that post-exposure paralysis as well as lung damage can occur as a result of insufficient intervals between repeated exposures. There is also evidence that repeated oxygen exposures which do not produce detectable impairment of pulmonary function may cause toxic effects in the eye or some other organ. The effects of repeated exposures of divers to increased oxygen pressures cannot be predicted accurately until appropriately designed animal and human studies are performed.

3. Mechanisms of Oxygen Toxicity

Numerous mechanisms have been advanced to explain the toxic effects of oxygen. These hypotheses include: enzyme inhibition, membrane damage, increased production of chemically reactive species, decreased energy metabolism, neurotransmitter inhibition, increased state of oxidation, inhibition of cell replication, and increased intracellular acidity. To date, no single hypothesis of the mechanism of oxygen toxicity has been accepted. In addition, the mechanism by which oxygen produces its toxic effects may differ in various tissues.

4. Factors Which Modify the Rate of Development of Oxygen Poisoning

Many factors modify the response to oxygen exposure. Increased age, higher temperature, various hormones, and some emotional stresses significantly decrease oxygen tolerance. In contrast, increased tolerance to oxygen exposure can be produced by a variety of procedures. For example, some animals which would die within three days of exposure to one ATA of oxygen may survive for many weeks if they have previously been exposed to 0.8 ATA of oxygen for a week.

Periodic, brief interruptions during oxygen exposure (for example, 20 minutes of oxygen, followed by 5 minutes of air) have been shown in man to be an effective means of delaying the onset of acute manifestations of both neurologic and pulmonary oxygen poisoning. Additional studies are needed to confirm the safety of this procedure and to determine whether the apparent protection it confers is extended to other forms of oxygen intoxication.

It has been shown that many chemical compounds decrease the toxic effects of oxygen in animals. These include: sulfhydryl compounds, acid-base buffers, antioxidants, neurotransmitters, metabolic intermediates, and enzyme inhibitors. Although these agents delay the onset of oxygen poisoning, none provides absolute protection, and their effectiveness in man is still undetermined.

5. Sensitivity to Oxygen Toxicity

It has been shown that individuals exhibit major differences in sensitivity to increased oxygen pressures. The reasons for such differences are not known, but they may be related to mechanisms which normally protect against oxygen toxicity. In addition, diseases which affect those parts of the lung or brain which are also affected by high oxygen pressures may make an individual more sensitive to oxygen poisoning. Studies show that several conditions that injure the lung hasten the onset of oxygen toxicity. It is imperative that methods for selecting divers and eliminating highly sensitive individuals from diving programs be developed.

III. RECOMMENDATIONS

Both applied and basic information is needed for better understanding of oxygen effects in diving. Well-designed studies of oxygen tolerance in man will yield results that have immediate application in the field. More basic information will permit evaluation of current concepts of oxygen poisoning and development of new ones. Animal experiments can also provide valuable guidelines for the design of safe and effective human studies.

The following recommendations are grouped into five interrelated areas of research which cannot be ranked by priority because information relevant to one area will be pertinent to the others as well. In addition, the recommendations do not separate studies of physiologic and toxic oxygen effects. It is sometimes impossible to distinguish between them, particularly with respect to the early subclinical phases of oxygen poisoning. As toxic effects develop, they are concurrent and interact with physiologic responses.

A. Mechanisms of Oxygen Toxicity

Knowledge of the basic mechanisms of oxygen toxicity would provide a scientific basis for selecting agents which might protect divers and others against oxygen toxicity. Furthermore, such information might lead to the development of techniques which would allow us to reject individuals who are particularly sensitive to oxygen toxicity and would therefore be bad risks as divers.

The cellular and biochemical events which precede functional alterations should be studied. These should include:* 1) biochemical systems which react with free radicals and peroxides; 2) methods of minimizing enzyme inhibition; 3) maintenance of normal levels of energy production; 4) maintenance of membrane integrity and function; 5) maintenance of normal intracellular oxidative states; and 6) cell replication.

The study of the action of different protective agents on the same biochemical functions which can be modified by oxygen toxicity may provide a method for defining common basic mechanisms responsible for the manifestations of oxygen toxicity. It is our view that the understanding of the basic mechanisms of oxygen toxicity will permit more rapid solution of many other problems delineated in this report.

B. Effects on Organ Systems and Functions

Toxic effects of oxygen on the lungs and brain have been studied more extensively than effects on any other organ. This is appropriate because lethal damage is caused by pulmonary oxygen poisoning during continuous exposure to oxygen pressures up to about two atmospheres and by both pulmonary and brain oxygen poisoning at higher pressures. An undesired consequence of the past emphasis on the lungs and brain is that little or nothing is known about toxic effects of oxygen on other vital organs and functions. There is evidence that multi-day exposures to oxygen pressures of less than one atmosphere or repeated shorter exposures to higher pressures may cause injury that is neither pulmonary nor neurologic in origin.

It is important to continue studies of the pulmonary and neurologic manifestations of oxygen poisoning and to initiate studies of oxygen effects in other organs. Both biochemical and functional effects of oxygen should be determined in all these areas. Efforts should be made to identify the earliest oxygen effects after the onset of exposure. Although changes in organ function must be preceded by cellular metabolic effects, the limitations of available techniques may require initial experiments which are designed to detect early functional alterations in some organs. The following specific recommendations for needed research are not intended to be inclusive. They represent some of the areas which deserve particular attention at this time.

---

*Numbers do not indicate priorities within categories in this section of the report.

Aspects of pulmonary oxygen poisoning which should be studied include: 1) endothelial cell interactions with circulating components; 2) the basis for differential sensitivity of lung cells; 3) methods for detection of early lung injury; 4) the effects of intermittent oxygen exposure; 5) alteration in cellular composition of the lung; 6) factors responsible for fibrotic and cystic changes following repeated or prolonged exposures; and 7) formation and reversal of pleural effusions.

Studies of neurologic oxygen poisoning should focus on cognitive, perceptual, psychomotor, visual, and auditory-vestibular function, the correlation of brain electrical and biochemical activity, and effects on peripheral nerves.

It is also important to study the effects of oxygen on other organs. Particular attention should be directed to: 1) the eye; 2) the heart, liver, and kidney; 3) smooth muscle and vasomotor activity and their effects on decompression; 4) the gonads and chromosomal effects; 5) the blood-forming system; 6) endocrine function, and 7) activation of the sympatho-adrenal system and interactions with pulmonary and neurologic oxygen poisoning.

In addition to studies of acute oxygen poisoning in the areas listed above, it is essential to evaluate the chronic effects of repeated exposures to high oxygen pressures or extremely prolonged exposures to less than one ATA of oxygen. The rate of recovery from oxygen poisoning should be studied in as many organs as possible, on the biochemical as well as functional level. There are few studies of chronic oxygen effects on the lungs and brain, and almost none which pertain to other vital organs. Because such repeated or prolonged exposures are likely to become more common in diving, these studies are critical for the health and safety of divers.

The rate of development of oxygen poisoning varies widely among species, which necessitates using human subjects when quantitative information relevant to man is required. For this reason, a high priority should be given to studies of oxygen poisoning in man. These studies can only be performed safely by using sensitive indices which detect toxic effects before they cause serious harm or irreversible damage. Identification and initial evaluation of such indices can often be accomplished with animal studies.

C. Modifying Factors

The alternation of brief exposures (minutes) to elevated and normal oxygen pressures is an effective means of delaying the onset of acute oxygen poisoning in man. Although this procedure is already used in diving operations and oxygen therapy, the durations of the alternating intervals have been chosen on the basis of animal experiments and have had minimal evaluation in man. Human studies are needed to develop optimal intermittency schedules at different oxygen pressures.

Alternation of much longer periods (hours to days) of oxygen and air breathing is an established method of increasing pulmonary oxygen tolerance in animals. Additional studies of this apparent adaptation are needed to determine if the effect is specific for oxygen poisoning or a non-specific reaction to pulmonary injury. It is possible that the apparently tolerant lung continues to be poisoned by oxygen.

A number of drugs have been used in animals to decrease the toxic effects of oxygen. The effectiveness of these agents in man, however, remains to be evaluated. It is imperative that clinical trials be instituted to determine their clinical effectiveness in man. It must be recognized that extensive pharmacological studies in animals must be performed before these agents will be approved for human use.

The effect of oxygen on the pharmacological action of therapeutic drugs is unknown. Because the action of drugs can be influenced by many factors, studies must be carried out to determine whether oxygen can affect the activity and toxicity of therapeutic drugs.

The interaction of stress with oxygen toxicity may be particularly important to divers; more information is required. Results of animal experiments show that reaction to stress can hasten the onset of oxygen poisoning. It is also important to study possible interactions of oxygen effects with other stresses to which the diver is exposed, such as exercise, temperature changes, carbon dioxide, and inert gas narcosis.

None of the available agents or procedures provides complete protection from oxygen poisoning. Evaluation of new approaches should be encouraged.

D. Sensitivity

Sensitivity to oxygen toxicity varies widely in different individuals and even in the same individual at different times. Better understanding of the basis for these differences may permit the development of procedures for selection of divers with increased oxygen tolerance. The possible influences of exercise, infections, alcohol, caffeine, and other drugs on inherent sensitivity should also be studied. Information about the basic mechanisms of oxygen poisoning should help to identify the basis for differential sensitivity.

E. Oxygen Therapy in Diving Accidents

A diver who develops decompression sickness during or after prolonged decompression with high oxygen levels may already have a significant degree of oxygen poisoning due to the depth and duration of his dive. Oxygen therapy will require additional exposure to toxic oxygen pressures. It is therefore necessary to optimize the oxygen therapy of decompression sickness both at shallow and great depths. The benefits and risks of a relatively brief exposure to a very high oxygen pressure must be weighed against the effects of a longer exposure to a lower oxygen level. Because the treatment of decompression sickness at great depth will necessarily require concurrent exposure to a high inert gas pressure, the influence of this condition on the effectiveness of oxygen therapy should also be evaluated.

IV. FACILITIES AND PERSONNEL

The investigators listed below, by virtue of their published or present work, are judged as qualified to perform research within one or more of the recommended areas. Their experience ranges from several years to recent entry into the field. Other qualified investigators may inadvertently have been omitted. We strongly urge that each application for support, whether or not its authors are listed here, be judged on its own merits.

1. Albert Einstein College of Medicine
   New York, New York

   R. M. Rosenbaum, M. Wittner

2. Colorado State University
   Hypo-hyperbaric Facility
   Department of Physiology and Biophysics
   Fort Collins, Colorado

   P. Hall

3. Duke University Medical Center
   Durham, North Carolina
   F. G. Hall Environmental Research Laboratory

   P. B. Bennett, H. A. Saltzman

Department of Radiology

A. P. Sanders, W. D. Currie

Department of Pathology

P. C. Pratt

4. The George Washington University Medical Center
Department of Medicine
Washington, D.C.

D. Massaro

5. Harvard University
Channing and Thorndike Memorial Laboratories
Harvard Medical Unit
Boston City Hospital
Boston, Massachusetts

G. Huber

6. Illinois Institute of Technology Research
Chicago, Illinois

J. D. Fenters

7. The Memorial Hospital
Pulmonary Division
Pawtucket, Rhode Island

R. A. Redding

8. Michigan State University
College of Osteopathic Medicine
East Lansing, Michigan

R. T. Houlihan

9. Mount Sinai Medical Center
Miami Beach, Florida

M. A. Sackner

10. Naval Medical Research Institute
National Naval Medical Center
Bethesda, Maryland

M. E. Bradley

11. Purdue University
Biological Sciences Division
Fort Wayne, Indiana

S. Gottlieb

12. Stanford Research Institute
Menlo Park, California

J. D. Hackney, M. J. Evans, C. E. Spier

13. Stanford University
Stanford, California

W. H. Northway

14. Virginia Mason Research Center
Seattle, Washington

B. D'Aoust

15. University of Arizona
College of Medicine
Tucson, Arizona

H. K. Fisher

16. University of California at Davis
Davis, California

A. Tappel, C. Chow, C. Cross

17. University of California at Los Angeles
Department of Medicine
Harbor General Hospital
Torrance, California

D. Tierney, M. Mustafa, J. Alexander

18. University of California Medical Center
San Francisco, California

J. A. Clements

19. University of Colorado Medical Center
Respiratory Care Unit
Denver, Colorado

T. L. Petty

20. University of Kansas
Department of Pharmacology and Toxicology
Lawrence, Kansas

M. D. Faiman, R. J. Nolan

21. University of Manitoba
Department of Pathology
Winnepeg, Manitoba, Canada

J. Y. R. Adamson, D. H. Bowen

22. University of North Dakota
Grand Forks, North Dakota

T. Akers

23. University of Oklahoma Medical Center
Departments of Pathology and Surgery
Oklahoma City, Oklahoma

J. J. Coalson, L. J. Greenfield, J. J. Beller

24. University of Pennsylvania Medical Center
Philadelphia, Pennsylvania
Departments of Animal Biology, Biochemistry, Microbiology, Ophthalmology, Physiology

R. E. Davies, H. Rasmussen, H. C. Davies, C. W. Nichols, A. B. Fisher

Institute for Environmental Medicine

C. J. Lambertsen, N. Haugaard, J. M. Clark, C. D. Puglia

Johnson Research Foundation

B. Chance

25. University of Saskatchewan
Department of Biochemistry
Saskatoon, Saskatchewan, Canada

J. D. Wood

26. Medical University of South Carolina
Department of Pathology
Charleston, South Carolina

J. D. Balentine

27. University of Washington School of Medicine
Anesthesia Research Center
Seattle, Washington

P. M. Winter

28. U.S. Air Force School of Aerospace Medicine
Brooks Air Force Base, San Antonio, Texas

J. C. Davis, T. J. Tredici

REFERENCES

1. Bean, J. W. 1945. Effects of oxygen at increased pressure. Physiol. Rev. 25:1-147.
2. Clark, J. M., and C. J. Lambertsen. 1971. Pulmonary oxygen toxicity: a review. Pharmacol. Rev. 23:37-133.
3. Davies, H. C., and R. E. Davies. 1965. Biochemical aspects of oxygen poisoning. In: Handbook of Physiology. Respiration, Vol. II, edited by W. O. Fenn and H. Rahn. Washington, D.C.: American Physiological Society.
4. Gottlieb, S. L. 1971. Effect of hyperbaric oxygen on microorganisms. Ann. Rev. Microbiol. 50:111-152.
5. Haugaard, N. 1968. Cellular mechanisms of oxygen toxicity. Physiol. Rev. 48:311-373.
6. Lambertsen, C. J. 1965. Effects of oxygen at high partial pressure. In: Handbook of Physiology. Respiration, Vol. II, edited by W. O. Fenn and H. Rahn. Washington, D.C.: American Physiological Society.
7. Nichols, C. W., and C. J. Lambertsen. 1969. Effects of high oxygen pressure on the eye. New Eng. J. Med. 281:25-30.
8. Stadie, W. C., B. C. Riggs, and N. Haugaard. 1944. Oxygen poisoning. Amer. J. Med. Sci. 207:84-114.
9. Winter, P. M., and G. Smith. 1972. The toxicity of oxygen. Anesthesiology 37:210-241.
10. Wood, J. D. 1975. Oxygen toxicity. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by D. H. Elliott and P. B. Bennett. Baltimore: Williams and Wilkins.

USE OF DRUGS AND OTHER MEDICAL TREATMENT UNDER HYPERBARIC CONDITIONS

Part #11 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Capt. Tor Richter, MC, USN (Chairman)
Commanding Officer
Naval Regional Medical Center
Camp Lejeune, North Carolina

Colin Jones, M.D.
Medical Advisor
B. P. Petroleum Development Ltd.
Aberdeen, Scotland

Tor Nome, M.D.
Hospital of Rogland
Stavanger, Norway

David A. Youngblood, M.D.
Medical Director
Oceaneering International, Inc.
Houston, Texas

TABLE OF CONTENTS and Organization for part 11

Use of Drugs and Other Medical Treatment Under Hyperbaric Conditions

I. Introduction 1

II. Problems other than Decompression that may Require Medical Treatment 1

- A. Problems Related to Diving Technique
  - 1. Types of Diving
  - 2. Environment(s)
  - 3. Technique-Related Medical Problems
    - a. Decompression ailments
    - b. Barotrauma
    - c. Heated suits
    - d. Gas problems
- B. Problems Related to Underwater Work
  - 1. Minor Trauma to Hands, etc.
  - 2. Backstrains and other Musculoskeletal Strains
  - 3. Crushing Injury of the Limbs, Abdomen, or of the Thorax
  - 4. Burns
  - 5. Electric Shock
  - 6. Welding Fumes
  - 7. Blast Injuries
- C. Pre-existing and Intercurrent Illness
  - 1. Pre-existing Illness
    - a. Chronic illnesses
    - b. Acute illnesses
  - 2. Intercurrent Illness
- D. Problems Related to the Diver's Working Environment
  - 1. Human Factors
  - 2. Environmental Factors

III. Present Day Treatment 4

- A. Treatment Complications
- B. Philosophy of Treatment
- C. Diagnosis
- D. Therapeutic Measures
- E. Suggested Drugs
- F. Intravenous Fluids
- G. Recommended Equipment List for Offshore Diving Operations
  - 1. Emergency Equipment Required Inside each Diving Bell and Deck Decompression Chamber
  - 2. Emergency Equipment Required On-Site and Immediately Accessible
    - a. Airway kit
    - b. Circulation kit
    - c. Drug kit
- H. Monitoring Equipment to Improve Hyperbaric Patient Care
  - 1. Circulatory System
  - 2. Respiratory System
  - 3. Other Systems

IV. Summary of Present Research 12

- A. Injuries Occurring Under Pressure
- B. Surgical Procedures
- C. Use of Anesthetics Under Pressure
- D. Therapeutic Use of Antibiotics, Antihistamines and other Drugs
- E. Sequelae of Normal Illnesses

V. Problem Areas and Priorities 13

- A. Summary Notes on Problem Areas
- B. Capabilities Required for Investigation of Problem Areas

I. INTRODUCTION

This report concerns medical support for divers in the oil and gas industry. Among the assumptions which underlie our findings and recommendations are the following: We predict that industrial divers will be diving at ambient pressure to depths of 2000 fsw, at least for the next decade. The majority of these dives will be shallower than 1000 fsw. Saturation diving will be extensively utilized. However, an increasing fraction of the diver's work, particularly at the deeper depths, will be conducted from manned or unmanned submersibles, and will only occasionally expose the diver to pressure. Divers who are working at ambient pressures will probably be using helium-oxygen; alternative gas mixtures, such as trimix, hydrogen, and crude neon may possibly affect the action of drugs, and they will require further consideration if they come into common use. We do not anticipate that liquid breathing will be used by industry. Present practice and equipment require that casualties be treated on-site until they can be decompressed.

Although there is a large body of research on decompression sickness, oxygen toxicity, and inert gas narcosis, studies of traumatic injury and infection are relatively few and confined to a small number of laboratories. Many of the special conditions of diving medicine are also common to other medical situations, such as industrial medicine, particularly in remote and isolated areas. Experience derived from the space program, heavy construction projects in remote areas, and maritime activities may serve as models for medical support programs for divers. These unusual situations have several factors in common: a young, healthy, medically screened population, increased probability of injury, difficulties in communication and transportation, and the lack of on-the-scene specialized medical care.

II. PROBLEMS OTHER THAN DECOMPRESSION THAT MAY REQUIRE MEDICAL TREATMENT

To achieve a systematic approach to this rather large area, we have decided to try to define the types of medical problems which pertain to divers. There are four main groups of problems: those related to diving technique (adjuncts to recompression), underwater work, the diver and his working environment, and problems caused by pre-existing and intercurrent illnesses.

A. Problems Related to Diving Technique

1. Types of Diving

There are four types of diving: SCUBA, surface-supplied, non-saturation, and saturation.

2. Environment(s)

We will consider both air and mixed gas diving, including heliox, trimix, and other mixes, and will also consider the use of specific diving equipment, such as heated suits.

3. Technique-Related Medical Problems

   a. Decompression ailments

      1) Neurological bends (Type II)
      2) Audiovestibular bends
      3) Recalcitrant bends

   b. Barotrauma

      1) Pneumothorax
      2) Acute sinusitis
      3) Acute otitis media

   c. Heated suits

      1) Skin Burns
      2) Skin infections

   d. Gas problems

      1) High CO_2
      2) High/low O_2
      3) Hydrocarbon contamination
      4) CO
      5) Other fumes (e.g., welding gases, diesel fumes, etc.)

B. Problems Related to Underwater Work

In oil field diving most of the work is of the heavy industrial type, and involves joining together heavy pieces of metal, cutting, welding, and some use of explosives. The following types of injury are likely to occur:

1. Minor Trauma to Hands, etc.

2. Backstrains, and other Musculoskeletal Strains

It should be remembered that the symptoms of these may well mimic decompression accidents.

3. Crushing Injury of the Limbs, Abdomen, or of the Thorax

4. Burns

5. Electric Shock

6. Welding Fumes

Blast Injuries, Caused by the Injudicious Use of Explosives or by Explosions Caused by the Buildup of Gas Pockets

C. Pre-existing and Intercurrent Illness

1. Pre-existing Illness

a. Chronic illnesses that have not been detected at regular medical examinations of divers call for on-site treatment. Medical conditions that might cause particular problems are those involving convulsive episodes, vomiting, and transient loss of consciousness. There is a particular need to detect drug misuse, and perhaps alcohol misuse, in the age group with which we are dealing.

b. Acute illnesses, such as coryza and influenza are well recognized ailments which can be exacerbated in a hyperbaric environment. Conditions causing bodily dehydration may also complicate or even potentiate decompression accidents. Such conditions include hangovers and gastroenteritis. With the increasing use of saturation diving, skin infections and skin rashes have become important economically; they have been the cause of several aborted dives in the oil fields.

2. Intercurrent Illness

Divers are subject to many medical or surgical conditions while under pressure, and treatment of illness and injury are greatly complicated by the long period of decompression required, particularly in saturation diving.

D. Problems Related to the Diver's Working Environment

1. Human Factors

a. Health of the diver

b. Conditioning and fitness of the diver

c. Training and experience

d. Fatigue, nutrition, relaxation

e. Psychological factors, e.g., panic

2. Environmental Factors

a. Atmosphere control in decompression chambers

b. Depth

c. Temperature

d. Visibility

e. Noise/vibration

f. Urgency

g. Other oceanic hazards

The medical profession must be prepared to deal not only with all of the illnesses and injuries which a young and active population engaged in heavy industrial work is subject to, but also with the complications of the diving environment--hyperbaric pressure, long decompression, and delay in reaching hospital facilities. The lack of qualified surgeons with any knowledge of hyperbaric conditions is a serious problem which must be corrected as soon as possible. The problem is schematically presented in Fig. 11-1.

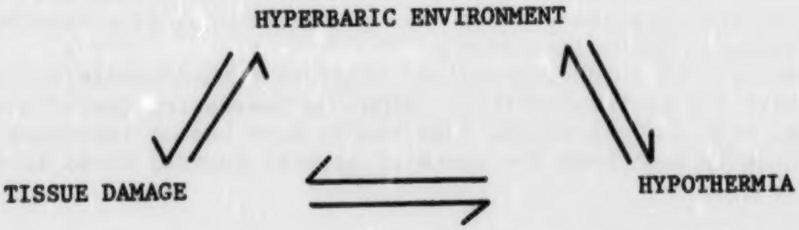
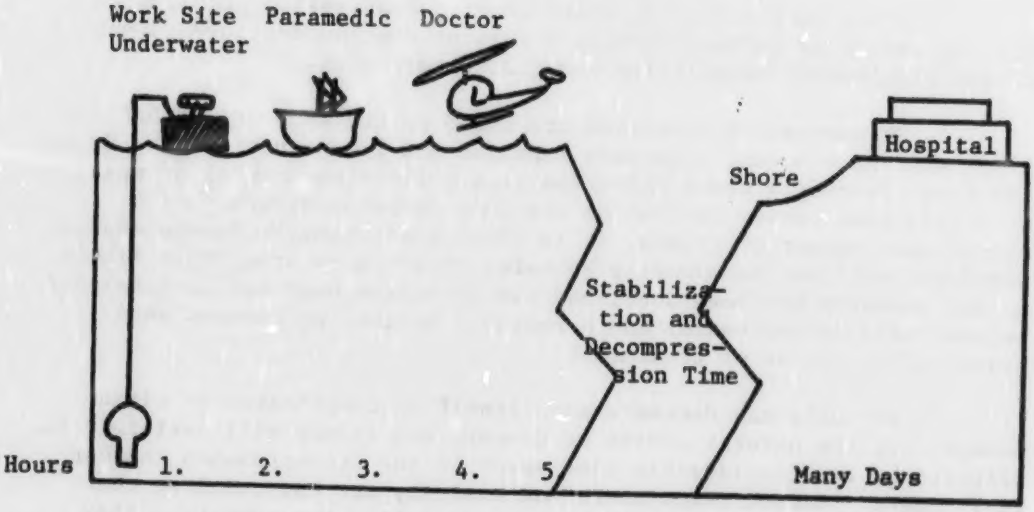


Fig. 11-1. Illustration of problem areas. An interrelated triangle of the complications caused by the interaction of environment, time, and distance from specialized medical help. Each of the three outlined areas has been extensively researched as a separate entity, but the implications of their interactions have not.

III. PRESENT DAY TREATMENT

A. Treatment Complications

Medical treatment of a diver under pressure on the work site is complicated by two factors: The work site is usually remote, and the time it takes to get a physician to the diver will be at least 4-5 hr. In modern oil field diving, decompression times will be long. Therefore, if a man is injured, the initial assessment and treatment must be undertaken by his diving companion, and then by a medic on the rig (see Fig. 11-2). These men, and in particular the medic, must be trained in advanced techniques to make the initial medical decisions logically and soundly, and then to act under the orders of a physician who will be in contact by radio or telex. Communications, both in accuracy of content and of transmission are vitally important to medical support of remote work sites.



1 hr - Diver Injured; 2 hr - Diver Enters DDC*; 3 hr - Paramedic Enters DDC*; 4 hr - Doctor Arrives on Rig; 5 hr - Doctor Enters DDC*; Many Days - Diver Enters Hospital.

***DDC = Deck Decompression Chamber**

Fig. 11-2. Time scale for treatment of an injured diver.

B. Philosophy of Treatment

There are two situations in a hyperbaric environment where medical treatment is necessary: as an adjunct to recompression therapy in decompression sickness, or in the treatment of illness or injury in a diver under pressure, who faces a very lengthy decompression period.

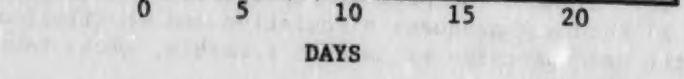


Fig. 11-3. Decompression time from saturation as a function of depth.

Since very little is known about decompression problems that will be caused by damaged tissue, treatment must be designed to ensure adequate pulmonary ventilation and tissue perfusion.

Decompression schedules are based on the assumption that the diver will have normal pulmonary function and tissue perfusion. Should the diver develop a chest infection (e.g., lobar pneumonia) or sustain an injury that causes partial or complete devascularization of a significant amount of tissue, it is clear that standard decompression schedules will not necessarily be safe. This is an area where little if any research has been done, and the physician must strike a balance between safe decompression and acceptable medical procedures when planning his course of treatment.

Not only may decompression itself be complicated by tissue damage, but the natural course of disease and injury will certainly be affected by the considerable time spent in the decompression chamber environment. Raised temperature and humidity are essential to the comfort of divers living in high pressure helium atmospheres. They are also associated with the rapid spread of bacterial infection (e.g., otitis externa). Healing of wounds and burns is considerably modified by immersion in water and by living in high humidity environments. Medical complications such as atelectasis, deep vein thrombosis, infections of wounds, urinary tract, and lung, skin ulceration, and infection due to inadequate skin perfusion are all considered probable complications of illness and injury in this environment. This is particularly the case since modern techniques of nursing care will not be available under pressure.

In summary, the physician must plan his treatment schedule very carefully, and resist the temptation to request a rapid decompression in order to get his patient to the surface when he is treating a patient under pressure.

He must make a medical evaluation while keeping in mind the lengthy decompression period and an environment where infections and other undesirable sequelae are likely. He must ensure that his patient's condition is stabilized, and that circulation and pulmonary function are as nearly normal as possible. He must decompress the patient cautiously, watching both for unexpected complications of decompression and for complications of the patient's medical condition.

C. Diagnosis

The state of knowledge today allows the following methods of diagnosis and treatment to be used in hyperbaric environments. All of them are unsophisticated by modern hospital standards, but all are designed to: 1) Make the patient comfortable and initiate specific therapy; 2) Maintain adequate circulation and ventilation; and 3) Make the decompression as safe as possible, given today's lack of adequate research.

The diagnosis of most diving illnesses and injuries, especially accidental trauma, should be obvious. Some, however, may require the application of various diagnostic techniques, such as the following:

- *Bacterial culture and sensitivity determination
- Blood hemoglobin determination
- Blood pressure determination
- Body temperature determinations
    - Oral
    - Rectal
- *Electrocardiography
- *Electroencephalography
- *Electronystagmography
- Flourescein staining of eye
- Hematocrit determination
- *Microscopic studies
    - Blood
    - Urine
- Ophthalmoscopy
- Otoscopy
- *pH determination
    - Blood
    - Urine
- Rhinoscopy

D. Therapeutic Measures

Physicians involved in offshore diving operations should be adequately trained and equipped to perform the following therapeutic measures:

- Airway maintenance
    - Oral
    - Endotracheal
    - Cricothyroid membrane puncture
- Aspiration procedures
    - Aspiration of hematoma or other fluid accumulations
    - Thoracentesis
- Drug administration
    - Oral
    - Topical
    - Local and regional
    - Systemic (intramuscular and intravenous)
- Eye patching
    - Foreign body removal from eye, nose, and larynx

---

*Presently not readily available on work site.

Immobilization of body part

Temporary
Indefinite duration

Incision and drainage

Intravenous fluid administration

Myringotomy

Nasogastric intubation

Suction

Upper gastrointestinal tract
Respiratory tract

Tourniquet application

Urinary bladder catheterization

Wound management

Dressing

E. Suggested Drugs

The types of drugs which should be available to physicians in the treatment of offshore diving illnesses or accidents are listed below. The effects of some of these drugs have had minimal evaluation under pressure; most have not. A thorough analysis of any alteration of pharmacological effect under hyperbaric conditions should be undertaken for at least one representative drug of each type, especially those marked,* which are only to be used with extreme caution.

Analgesic

*Non-gaseous anesthetics,
including local and i.v. techniques

*Antiarrhythmic

Antibacterial

Antimycotic

Antacid

*Heparin

Anticonvulsant (Diazepam)

Antihistamine

*Cortico-steroids, systemic

Antipyretic

Antitussive

*Bronchodilator

*Cardiac glycoside

Nasal decongestant

Diuretic (e.g., Lasix)

Antidiarrheal

Antiemetic

Tranquilizer (e.g., Diazepam)

*Vasopresser (Aramine)

F. Intravenous Fluids

Recognizing that circulatory support is fundamental in the treatment of low-perfusion states, the committee recommends that the following types of intravenous fluids be available on-site during offshore diving operations:

Saline, Isotonic

Glucose in water, 5%

Ringer's lactate solution

Bicarbonate solution, 4.2%

Supplemental potassium solution

Plasma-expanding agents (e.g., dextran, plasma)

Mannitol solution, 10%

Low-molecular weight dextran (i.e., Rheomacrodex)

G. Recommended Equipment List for Offshore Diving Operations

The committee agrees that some degree of standardization of emergency equipment required during offshore diving operations is desirable. The following list is the recommended minimum:

1. Emergency Equipment Required Inside each Diving Bell and Deck Decompression Chamber

a. Tourniquet

b. Pressure dressing

c. Thoracentesis needle and non-return valve device (present Australian government requirement)

d. Brook's Airway

e. Drinking water, 1 liter per man

f. High-carbohydrate survival rations

g. Man-powered CO_2 scrubber

Antidiarrheal
Tranquilizer (e.g., Diazepam)

Antiemetic
*Vasopresser (Aramine)

F. Intravenous Fluids

Recognizing that circulatory support is fundamental in the treatment of low-perfusion states, the committee recommends that the following types of intravenous fluids be available on-site during offshore diving operations:

Saline, Isotonic

Glucose in water, 5%

Ringer's lactate solution

Bicarbonate solution, 4.2%

Supplemental potassium solution

Plasma-expanding agents (e.g., dextran, plasma)

Mannitol solution, 10%

Low-molecular weight dextran (i.e., Rheomacrodex)

G. Recommended Equipment List for Offshore Diving Operations

The committee agrees that some degree of standardization of emergency equipment required during offshore diving operations is desirable. The following list is the recommended minimum:

1. Emergency Equipment Required Inside each Diving Bell and Deck Decompression Chamber

a. Tourniquet

b. Pressure dressing

c. Thoracentesis needle and non-return valve device (present Australian government requirement)

d. Brook's Airway

e. Drinking water, 1 liter per man

f. High-carbohydrate survival rations

g. Man-powered CO_2 scrubber

2. Emergency Equipment Required On-Site and Immediately Accessible

a. Airway kit

1) Oropharyngeal airway

2) Manual suction device

3) Endotracheal tubes, cuffed, with 50 ml sterile water, a 20-cc syringe, and a positive locking clamp device

4) Hand bag resuscitator with oxygen or other treatment gas reservoir, plus an appropriate length of connecting hose and a valved adaptor for the decompression chamber built-in breathing system (BIBS)

5) Cricothyreotomy tray

6) Thoracentesis needle and non-return valve device

b. Circulation kit

1) Pressure dressing

2) Tourniquet

3) Hemostats (sterile), 2 each

4) Swaged needle-suture (sterile)

5) Needle holder (Magill)

6) Venous cutdown tray

7) Assorted flexible intravenous catheters

8) Infusion sets (2)

9) Lactated Ringer's solution, 500-ml bag

10) Rheomacrodex (low molecular weight dextran) 1 bottle

c. Drug kit - injectables in preloaded syringes

1) Demerol

2) Diazepam

3) Dexamethazone

4) Aqueous Epinephrine 1:1000

H. Monitoring Equipment to Improve Hyperbaric Patient Care

Once treatment has been initiated and decompression has begun, the problems of monitoring the patient's progress must be tackled. At present, traditional methods of observing clinical signs must be used. These methods are inadequate, and we strongly recommend that research on adapting modern intensive-care monitoring to the hyperbaric environment be undertaken. The experience of NASA in this field should be invaluable.

The improvements required are all related to patient monitoring, since the early detection of complications both of decompression and of the patient's clinical condition is vitally important in planning any necessary modifications of decompression or medical treatment.

The development of the following monitoring capability is recommended:

1. Circulatory System

   a. Determination of electrolytes, blood gases, and pH

   b. Central venous pressure

   c. A means of assessing changes in tissue perfusion (possibly venous O_2 measurements)

   d. Localized bubble detection (to detect complications arising in poorly vascularized tissue)

2. Respiratory System

   a. Means of measuring changes in perfusion/diffusion ratios

   b. Expiratory CO_2

3. Other Systems

   a. Electronic monitoring of Electrocardiogram, Electroencephalogram, Electronystagmogram, Temperature, Audiometry

These monitoring facilities are already routine in research facilities, but they should be adapted for field use.

   b. Bacteriology and simple hematology are already possible, given an adequate logistics system.

If pulmonary function and tissue perfusion could be monitored accurately, the effect of tissue damage on the decompression schedule could be assessed, and decompression modified as necessary. The development of medical complications would normally be detected by clinical examination.

Consideration of the implications of the tissue damage/decompression problem leads to the conclusion that decompression will probably be longer than normal if the patient is to avoid serious medical complications.

IV. SUMMARY OF PRESENT RESEARCH

A literature search of this topic is difficult because many publications are not indexed. References have been selected from among those furnished to the committee in abstract and they have been supplemented by sources known to the committee. A more complete bibliography could be assembled, though with difficulty. We believe that most of the relevant literature in English has been surveyed, but are not certain this is so.

A. Injuries Occurring Under Pressure

The vast majority of industrial injuries under pressure go unreported. Anecdotal information indicates that they consist of cuts, burns, and blunt trauma expected in heavy industry. An occasional spectacular injury (1) is reported, but even here significant medical details are omitted. Reporting will continue to be unsatisfactory unless it is made mandatory.

The United States Navy maintains a computer index of diver injuries in a data bank maintained by the Naval Safety Center, Norfolk, Virginia. The Longitudinal Health Survey of divers and submariners (7) being conducted at the Submarine Medical Research Laboratory, Groton, Connecticut, includes data on trauma and infection in sections on morbidity and mortality. The Diving Accidents Survey conducted by the University of Rhode Island (8) applies almost exclusively to sport and scuba diving.

The Navy's *Deep Submergence Biomedical Plan* outlines naval research in underwater medicine (12). It contains a section on blast injury and references to injuries caused by venomous marine creatures.

B. Surgical Procedures

Pressurized surgical suites for the conduct of hyperbaric oxygen-supported surgery exist in medical centers throughout the world. Experience has proved the feasibility of this technique, and also demonstrated its hazards (6). Some of these surgical facilities are components of hyperbaric chamber complexes used in research and training, and these are the most likely choices for treatment of divers requiring surgery while under pressure. There is only one instance known to the committee (1) where emergency surgery was conducted in an operating recompression chamber. The procedure was performed with immense difficulty.

C. Use of Anesthetics Under Pressure

Though some animal studies suggest that hyperbaric pressures reverse the anesthetic effects of certain agents (3), these effects have not been observed in present clinical practice at relatively low pressures. Anesthesia in the compression environment has rarely been attempted; instead, intravenous and local techniques have been employed.

D. Therapeutic Use of Antibiotics, Antihistamines and other Drugs

Well-controlled animal studies on the effects of morphine, tripelennamine, pentobarbital, lidocaine, ethanol, ouabain, and digoxin to depths of 600 fsw have not shown important differences in their pharmacologic action or LD_{50} (mean lethal dose) when compared to controls (9, 10). Anecdotal reports of bizarre symptoms following the administration of medication in the field exist, but these are of uncertain reliability. A few studies have suggested that the action of antibiotics is altered *in vitro* at high pressures, but that the effect is not large. The isolation of penicillin-resistant *D. pneumoniae* from divers suffering upper respiratory infections has been reported (5).

E. Sequelae of Normal Illnesses

Convalescence from chronic skin infections, and especially otitis externa, is prolonged in the diving environment. Improvement may be impossible to achieve without return to the surface. There is a clinical suspicion, not well documented, that viral infections may be more severe in divers than would otherwise be expected. Animal studies involving experimental respiratory infections have been inconclusive (2).

V. PROBLEM AREAS AND PRIORITIES

In this section the committee has attempted to indicate problem areas derived from the preceding discussion and to assign a numerical priority to each. This list includes some subjects which are properly the concern of other working groups. We hope such duplication will reinforce their recommendations, and inform subsequent groups of our opinions. The emphasis placed on applied research, education, training, and systems development probably reflects the practical bias of the committee, whose members are primarily concerned with direct delivery of medical services to the industrial diving community.

Priorities are based on: importance of the project, practicability, and specificity.

Each problem was assigned a numerical figure from 1 to 4, 4 being the highest score. Total point score was derived by assigning importance and practicability three times the weight of specificity. Definitions follow:

Importance. In calculating importance we included a risk factor and the number of people involved in such risks, as well as the medical and economic cost of the probable mortality and morbidity involved in the problem. The loss of work time due to casualties or the abortion of a dive for medical reasons was included in our cost estimates.

Practicability. The committee weighed each project in relation to the availability of research facilities and personnel to carry it out. An additional consideration was the project's relative complexity; for example, data collection, which requires widespread cooperative effort, would make a project less practicable. Actual fiscal costs of the projects were not included.

Specificity. This factor is an attempt to evaluate how specifically the problem under consideration is related to the underwater oil and gas industry. If, for example, the problem is also being investigated in other research and development programs, it was rated as less specific to this plan. Representative programs covering or overlapping the problem areas under consideration include those of the U.S. Navy, foreign governments, NASA, etc. In instances where parallel programs exist, cooperative programs should be considered.

We have also included a general confidence factor in the following table. This factor reflects the degree of unanimity among committee members on a particular problem, as well as the committee's estimate of its own ability to render an authoritative opinion on that problem. We did not consider whether support of a particular project would generate or sustain research capabilities in general, or whether certain projects would encourage other agencies to spend money. These and other factors would undoubtedly influence a program manager in the allocation of research funds.

The committee wishes to emphasize that the numerical scoring and weighing factors are subjective, and its use of numbers should not imply that these priorities can be stated precisely. Hence, the table may well need refinement, and will certainly require revision with the passage of time. It is offered as a rough guide for assigning priorities when making decisions.

Table 1. Medical Research Priorities

Rank	Problem Area	Importance	Practicability	Specificity	Total	Confidence
1.	Loss of Consciousness in Divers; Epidemiologic Study	4	4	2	26	high
2.	Transfer of Patients Under Pressure	3	4	4	25	high
3.	Effects of Tissue Damage on Decompression	3	4	3	24	high
4.	Training Paramedical Personnel	4	3	2	23	high
5.	Training Divers in Medical Emergencies	3	4	2	23	high
6.	Diver Monitoring and Communications	4	3	2	23	high
7.	Microbiology, Especially Skin Infection	4	2	3	21	low
8.	Effects of Drugs and Anesthetic Agents	2	4	2	20	high
9.	Data Collection, Storage, Retrieval	3	2	1	16	intermediate
10.	Training Medical Specialists	2	1	2	11	high

For an explanation of the respective weights of each of these factors used in calculating priorities, see text, p. 11-13.

A. Summary Notes on Problem Areas

1. Loss of Consciousness in Divers; Epidemiologic Study

Loss of consciousness appears to be the most important single cause of working diver mortality. Present hypotheses about the causes are not sufficiently researched; an epidemiological study is urgently needed. We understand that a small research program is being planned in Aberdeen, Scotland.

2. Transfer of Patients Under Pressure

Treatment of medical problems in hyperbaric environments will lengthen decompression times, perhaps extensively. The effects of longer decompression on the course of disease or injury make an extremely strong case for the development of a transfer system and a hospital-based treatment facility for divers. The economic implications of greater down times of offshore installations are also great.

3. Effects of Tissue Damage on Decompression Time

Nothing is known on this subject, though it is of great importance in treating an ill or injured diver.

4. Training Paramedical Personnel

Work site medical coverage is very important, since medical problems will have to be dealt with for several hours before a doctor arrives. A training program for paramedics is needed.

5. Training Divers for Medical Emergencies

We recommend that all divers be trained in basic first aid.

6. Diver Monitoring and Communications

Accurate reporting of clinical problems and reliable patient monitoring during treatment would be a significant advance over present-day medical capabilities. Many of the required monitoring techniques have already been developed in research units. They need to be adapted to field use.

7. Microbiology, Especially Skin Infection

Infection of the skin, especially otitis externa, is the greatest single cause of morbidity in working divers. Some bacteria are known to develop resistance to antibiotics under pressure. Resistant strains of bacteria cause serious consequences if they infect a wound or cause systemic infection.

8. Effects of Drugs and Anesthetic Agents

More work is needed on the action of drugs under pressure, and also on techniques of anesthesia. Work on assisted respiration should be included in such studies.

9. Data Collection, Storage, and Retrieval

Epidemiological study is required for an accurate definition of the problems that occur. Design and operation of a comprehensive and long-term study may be difficult. A pilot study of one operational area may be of value. This committee's difficulties in assembling a useful bibliography reflect the difficulties in this area.

10. Training Medical Specialists

The committee prefers a small number of active physician-medical specialists with good paramedics and communications, to a large number of superficially trained physicians.

B. Capabilities Required for Investigation of Problem Areas

1. Loss of Consciousness in Divers; Epidemiologic Study
    - a. Familiarity with operational diving
    - b. Understanding of diving physiology
    - c. Epidemiological experience
2. Transfer of Patients Under Pressure
    - a. Systems analysis
    - b. Design and engineering capability for diving systems
    - c. Emergency medicine and surgery
3. Effects of Tissue Damage on Decompression Time
    - a. Pressure chamber
    - b. Experimental animals
    - c. Surgical capabilities
4. Training Paramedical Personnel
    - a. Medical school or medical school-affiliated hospital
    - b. Pressure chamber complex

c. Physicians and staff experienced in

  1) operational diving
  2) emergency medicine
  3) medical care in remote areas

5. Training Divers in Medical Emergencies

Recognized first-aid training program, e.g., St. John's Ambulance or Red Cross

6. Diver Monitoring and Communications

  a. Pressure chambers

  b. Diving physiologist

  c. Communications engineer

7. Microbiology, Especially Skin Infection

  a. Bacteriological research capability

  b. Pressure chamber

  c. Dermatologist

  d. Field studies

8. Effects of Drugs and Anesthetic Agents

  a. Pressure chamber

  b. Experimental animals

  c. Appropriate scientific and medical specialists

9. Data Collection, Storage, Retrieval

  a. Librarian experienced in data retrieval

  b. Epidemiologist

  c. Computer access

10. Training Medical Specialists

Access to diving operations in addition to the facilities listed under Training Paramedical Personnel (see above).

This report amplifies and overlaps previous analyses of biomedical support of manned underwater operations, such as the U.S. Navy's Deep Submergence Biomedical Development Plan (12). Our emphasis on trauma and quick access to the injured or acutely ill diver-patient reflects the concern which we feel as we watch the techniques of heavy construction being transferred to underwater environments.

Any plan evolved should make maximum use of existing executive agencies and laboratories. What the nation does not need is further fragmentation of its underwater programs.

REFERENCES

1. Carter, L. H., and G. A. Goldsmith. 1970. The ordeal of Donald Boone. *Nutr. Today* 5:2-9.
2. Gordon, F. B. and James D. Gillmore. 1974. Parabarosis and experimental infections. *Aerospace Med.* 45:241-248; 254-256; 257-262.
3. McDowell, D. G. 1964. Anesthesia in a pressure chamber. *Anaesthesia* 19:321-336.
4. Medical Aspects of Small Submersible Operations. 1975. *Seventh Undersea Med. Soc. Workshop, Rept. No. WS: 7-1-75.*
5. Raymond, L., D. Kingsbury, and J. F. Duncan. 1971. Pencillin resistance to D. *pneumoniae* in upper respiratory infections associated with diving. *Aerospace Med.* 42:191-198.
6. Saltzman, H. A. 1967. Hyperbaric oxygen. *Med. Clin. N. Am.* 51:1301-1314.
7. Sawyer, R. N., and J. H. Baker. 1972. The longitudinal health survey. I. Description. *U.S. Navy Submar. Med. Res. Lab., Rept. NSMRL 733*, Dec. 14, 1972.
8. Schenck, H., Jr., J. McAniff, M. L. Schenck, and H. Schenck. 1972. *Diving accident survey 1946-1970, including 503 known fatalities.* Kingston, R. I.: Rhode Island Univ. Dept. Ocean Eng., Rept. 5.
9. Small, A. 1970. The effect of hyperbaric helium-oxygen on the acute toxicity of several drugs. *Toxicol. Appl. Pharmacol.* 17:250-261.
10. Small, A., H. W. McElroy, and R. S. Ide. 1971. Studies of the electrocardiogram and toxicity of cardiac glycosides in animals exposed to hyperbaric helium. *Toxicol. Appl. Pharmacol.* 20:44-56.
11. Tansey, W. A., LCDR, MC, USNR, and Kenneth Olson, LCDR, MC, USNR. 1975. *Naval Submarine Med. Res. Lab., Rept. No. 815.* Bureau of Medicine and Surgery, Navy Dept., Research Work Unit MF51.524. 006-9025.42, Sept. 8, 1975.
12. U.S. Navy. 1971. *Development Plan for Project M 43-06X; Deep Submergence Biomedical Development.* Bureau of Medicine and Surgery, Nov. 1971 (Official Use Only).
13. U.S. Navy. 1973. *U.S. Diving Manual*, Navships 09994-001-9010, Sept. 1973.

HIGH PRESSURE NERVOUS SYNDROME

Part #12 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Peter B. Bennett, Ph.D. (Chairman)
Co-Director, F. G. Hall Environmental Research Laboratory
Duke University Medical Center
Durham, North Carolina

Arthur Bachrach, Ph.D.
Chairman, Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, Maryland

Ralph Brauer, Ph.D.
Institute of Marine Biomedical Research
Wilmington, North Carolina

Jean-Claude Rostain, Ph.D.
Institute de Neuro Physiologie and Psycho Physiologie
Cedex 2, France

Lawrence Raymond, M.D. (Advisor)
Assistant Head, Pulmonary Branch
National Naval Medical Center
Bethesda, Maryland

TABLE OF CONTENTS and Organization for Report #12

High Pressure Nervous Syndrome

I. DEFINITION OF THE PROBLEM 1

II. AN HISTORICAL REVIEW OF HPNS 2

III. ASPECTS OF HPNS IN HUMANS 3

A. Tremors

1. Methods of Tremor Measurement
2. Causes of Tremor
3. Etiology of Tremors: The Question of Compression Rate

B. EEG Changes and Performance Measurements

1. Measurement of EEG Effects

C. The COMEX Exploratory Dives

1. Clinical Signs Observed by the COMEX Group
2. COMEX Conclusions

IV. ASPECTS OF HPNS IN ANIMALS 31

A. History of Animal Research

B. Description of HPNS in Animals

C. Stages of HPNS in Animals

D. Individual Variations in Animals

E. Electrophysiological Effects in Animals

F. Absence of Generalized Autonomic Effects in Animals

G. Temperature Regulation in Animals

V. EXPERIMENTAL MODIFICATION OF HPNS IN ANIMALS 40

A. Temperature

B. Noise

C. Compression Rate

D. Pharmacological Studies and Reserpine

E. Neuroanatomic Considerations

VI. PREVENTION OR AMELIORATION OF HPNS 44

VII. ETIOLOGY OF HPNS 54

A. Oxygen

B. Gas-Induced Osmosis

C. Diluent Gas

D. Direct Effects of Hydrostatic Pressure

E. Carbon Dioxide

VIII. RESEARCH NEEDS 62

A. Immediate Applied Research Needs

1. Diagnosis of HPNS Stages
2. Vigilance, Microsleep, Sleep Disturbance
3. Vestibular System Involvement
4. Visceral and Autonomic Effects

B. Practical Problems

1. Selection of Personnel
2. Compression Profiles
3. Accommodation and Adaptation
4. Temperature Effects
5. Environmental Setting: Open-Sea vs. Chamber
6. Prophylaxis and Treatment

C. Implications of HPNS for Deep Diving

1. Performance Decrement
2. Residual Effects of HPNS Exposures
3. Choice of Optimal Procedures

D. Basic Mechanisms Requiring Research

1. Anatomical Sites of HPNS
2. Neurophysiological Substrates
3. Biophysical and Biochemical Mechanisms
4. Role of Neurotransmitters
5. Compression-Rate Dependence
6. Comparative Physiology: Relations

IX. PRIORITIES 69

Appendix A

I. DEFINITION OF THE PROBLEM

When all vertebrates, including man, are exposed to pressures greater than 15 ATA, either in the dry hyperbaric environment of a pressure chamber or by the hydrostatic pressure of actual submersion, signs and symptoms appear which include tremors of the extremities, more severe myoclonic jerking, fatigue, and ultimately convulsions. In association with these characteristics, there are changes in the electrical activity of the brain and, at times, nausea, dizziness, vertigo, and feelings of euphoria. These can cause a decrement in the performance of deep divers, although convulsions have not been seen at the pressures to which man has been exposed to date (equivalent to 2001 fsw). However, such convulsions have been seen in other primates (monkeys) and it is pertinent that, in the case of animals, death may ensue if pressures are increased still further.

In humans the signs and symptoms associated with high pressure diving comprise the High Pressure Nervous Syndrome (HPNS); they are affected by the rate of compression as well as by the hydrostatic pressure attained. The faster the rate of compression and the higher the pressure, the worse the signs and symptoms. Thus, the ability of divers to be compressed in a reasonable time for a particular job and to be fit to work is limited. At depths greater than 1500 fsw, even with very long compression times of many days and with slow rates and stages which have proved effective in ameliorating HPNS, signs and symptoms of HPNS remain which may affect the performance, health, and safety of the deep diver.

HPNS comprises two factors, those associated with compression rate and those associated with hydrostatic pressure. As will be described, much is known of the signs and symptoms related to each of these aspects but the complex interaction of these phenomena is unclear. Also unknown are the optimum rates of compression with or without stages or, indeed, how long the stages should be for the safe exposure of divers to great depths.

A further important factor is that since the etiology of HPNS is at present speculative, it is not known if any permanent damage to the brain results from the frequent exposure of divers to HPNS when they operate for a period of time from an oil rig in very deep waters. Under these circumstances, HPNS may well determine the limits of the conditions to which man may be exposed while performing useful work under the ocean. The depths at which offshore oil rigs are beginning to work are increasing rapidly (involving jobs presently at 1200 fsw, within one year at 1500 fsw, and even a few jobs currently available at 2000 fsw or deeper). (See Appendix A) The divers on oil rigs carry out a large number of tasks essential to the operation of the rig; HPNS thus constitutes a formidable problem for the growth of the offshore oil industry and a challenge to the ability of the nation to utilize its deep offshore resources in its quest for energy.

Most of the research to date has been carried out only in pressure chambers under laboratory conditions. This research has been limited by the small number of laboratories, pressure chambers of adequate depth, and skilled scientists and clinicians trained to carry out such work. Further, much of the research during the 1960's--when it became apparent that man could dive to 1000 fsw or deeper--was funded primarily by the navies of the world. The navies had limited interests in very deep diving and these programs were only funded conservatively, since it was believed there would be little real need for man at such depths. The rapid growth of the offshore oil industry has, however, presented a new and urgent reason for man to dive safely and efficiently to very great depths.

II. AN HISTORICAL REVIEW OF HPNS IN MAN

In 1965 the Royal Naval Physiological Laboratory (RNPL) at Alverstoke, Great Britain, was conducting a series of deep chamber dives to depths of 600 to 800 feet of sea water (fsw). During these dives the subjects developed coarse tremors, involving the extremities or even the whole body, accompanied by nausea, occasional vomiting, dizziness, and vertigo. This condition led to a severe decrement in psychomotor performance, especially in any task requiring manual dexterity, as well as documented decrements in cognitive function (Fig. 12-1).

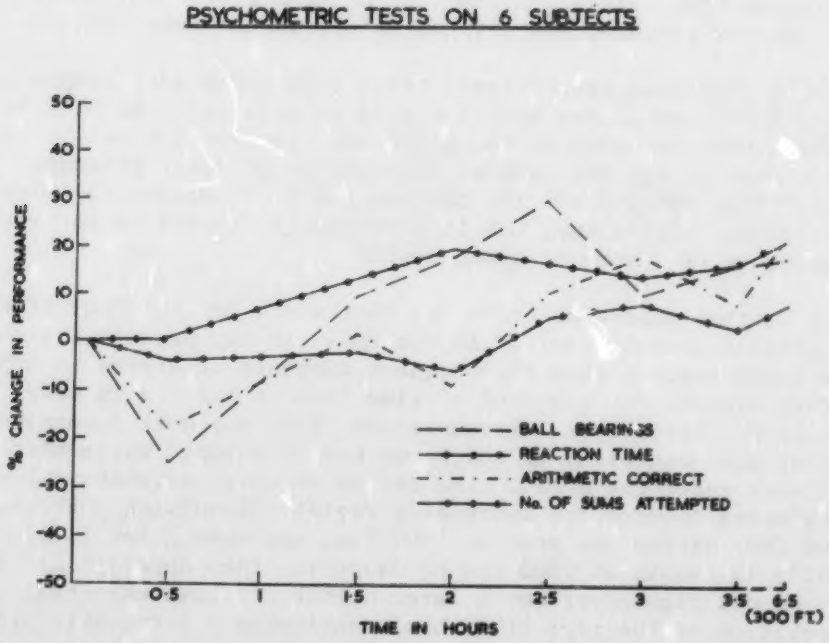


Fig. 12-1. Tests of performance efficiency on six men at 19.2 ATA (600 ft) breathing 5/95% oxygen-helium (Bennett 1965; 1967).

However, after some 90 min at depth, subjects gradually returned to normal (8, 16). Subsequent experimental dives confirmed the existence of this condition (13, 72, 153) and noted a relationship between the symptoms and the rate of compression. It was demonstrated that if compression rates were kept sufficiently slow, symptoms were kept to a minimum (119).

In 1968 a French dive to 1189 fsw was aborted because of the development of electro-encephalographic changes associated with somnolence and confusion in the divers (63). Similar changes had been seen earlier in animal experiments just before the onset of generalized seizures (27). This complex of tremors, EEG changes, and somnolence was termed the High Pressure Nervous Syndrome (HPNS) (25, 62a). Since that time numerous deep dives, animal experiments, and pharmacological studies have been conducted in an attempt to elucidate the nature of this syndrome, its etiology, and methods to counteract it. The purpose of this section is to summarize these studies, attempt to draw conclusions based on current knowledge, and point out specific problems that must be solved before man's diving capabilities can be extended to great depths.

III. ASPECTS OF HPNS IN HUMANS

Various general descriptions of HPNS have been published (25, 63, 58a, 59c, 59b). These descriptions agree regarding the basic characteristics of this syndrome. Compression rate seems to affect the onset of symptoms and their severity. For example, when the French Physalie series of dives used a compression rate of approximately 8.25 ft/min without rest stops, the following pattern was seen: tremors appeared at 21 ATA; electroencephalogram (EEG) changes began at 25 ATA; motor incoordination developed at 33 ATA. By 35 ATA the subjects were experiencing loss of alertness, and by 36 ATA they had developed extreme indifference and decreased comprehension. In general, symptoms have tended to abate rapidly with the beginning of decompression (63), although EEG changes may persist for somewhat longer. It has been the consensus of a number of authors that there are no residual effects. Personal observations by subjects have corroborated these patterns (25). Brauer described tremors which interfered with note-taking at depth, a certain degree of disorientation, and confusion in reading dials. However, residual effects after dives were not noted.

Neuromuscular signs and symptoms tend to be the initial manifestations of HPNS.

A. Tremors

In early experiments in man and animals reported by Zaltsman (153) and Bennett (10, 11) the onset of helium tremor was related to the partial pressure of helium rather than pressure itself. However, similar tremors have been reported since in experiments by

Lever, Miller, Paton, and Smith (96) using only hydrostatic methods without helium. Zaltsman noted that tremor was more important in "dry" than "wet" dives, as Bennett and Dossett (16) also observed when comparing simulated dry descents to 600 fsw with ocean dives in the Mediterranean in the mid-1960s. It is believed that tremor is facilitated by hyperthermia, especially when the chamber temperature is increased from 18-20 °C to 25-30 °C, as may occur in compression. The tremor usually disappears at depth, when the chamber temperature has fallen to room level.

During the COMEX Physalie V experiment in 1970, two divers spent 12 days reaching a maximum depth of 1,706 fsw after 3 days of compressing in stages. Some symptoms of HPNS were noted. At 1,510 fsw and deeper, "static tremor" as well as "kinetic tremors and dysmetria" were observed.

During Physalie V the tremor was measured by an accelerometer placed on the middle finger of the right hand (59b, 131a). It can be inferred from these papers that static tremor of fast frequency (about 10 Hz) occurs in the extremities and is identical to the trembling or "helium tremor" described by Bennett (10, 11) and by Brauer et al. (31), while "kinetic difficulties" involve "saccadic gestures" and "dysmetria." Fructus and Vigreux (59b), in their summary of the French deep dives, reported HPNS symptoms such as tremor, lowered vigilance, and electroencephalographic (EEG) anomalies, including increased theta activity. These effects were found also to a lesser degree in the 1,500 fsw dive at the Royal Naval Physiological Laboratory (RNPL), Alverstoke, England, in 1970, reported by Bennett and Towse (17a, 17b). Accordingly, while recognizing tremor as a potential problem--indeed a danger signal that may presage unconsciousness--Fructus and Vigreux (59b) do not believe it will seriously interfere with work, especially at greater depths.

During the Sagittaire II simulated dive to 1,640 fsw in 1972, the first symptoms of HPNS were observed in the range of 1,000 to 1,200 fsw. An increase in symptoms was noted down to 1,640 fsw, where the syndrome stabilized after the first 40 hr of bottom time. During the remaining 60 hr of bottom time, there was no significant improvement until the divers were brought into the 1,000 fsw range during decompression. The symptoms observed were the same as those reported in the 1968 COMEX dives: "static tremor... muscular jerks, lack of coordination of certain movements, more or less marked EEG changes, some of which denote a lessening of awareness (62)." In contrast, fairly good persistence of motor, psychomotor, and intellectual faculties in performing specific tasks was reported. COMEX investigators state that these disorders must not be underestimated. They were controlled in the Sagittaire II dive by modifying the compression, which was carried out at a decreasing speed to 14 ft/hr on arrival at 1,640 fsw (61, 132).

The report on the Physalie V dive (44) also illustrates a measurement problem for investigators: the subjective nature of defining compression in evaluating reports of neuromuscular decrement and tremors. For example, Fructus and Agarate (58a) developed a compression method for Physalie V which "included three fast compression periods (at 1 meter per minute...)." "Fast" in this case was a rate approximately one-third the 100 ft/min compression rate used in the RNPL dives. This point is also illustrated by Bennett, who refers to a study comparing rapid rates of compression with "the normal slow rates of 100 ft/min" (12).

1. Methods of Tremor Measurement

The means by which tremor and neuromuscular decrement are measured are often not indicated in studies. Subjective observation or objective recording are rarely differentiated, and even objective methods vary. For example, in Bennett's early experiments (13) the subject was required to pick up ball bearings one at a time with a forceps and place them in a small tube; this was used as one measure of neuromuscular decrement related to tremor. In later studies (20), a transducer was also attached to the subject's middle finger, which, when extended, yielded a measurement of postural tremor. This method is similar to that reported by Rostain (173). Bennett and Dossett (16) and others such as Krasberg (86) and Rashbass (125) also used ball bearing tests to quantify neuromuscular decrement in a manner similar to these earlier experiments. Langley (93) assessed tremor with a middle-finger transducer which operated on the principle of electromagnetic induction. When the magnetic ring on the diver's hand was placed over the induction coil, tremor induced current in the coil.

Bachrach, Thorne, and Conda (3) reported the use of a muscle-force transducer which measured an intentional tremor during compression and decompression in the 1970 Makai Range 520-fsw saturation dive. Use of a force transducer to measure response variation within a specified band allowed the measurement of a microtremor superimposed upon a muscle response held within the force band. All three subjects showed normal tremor when analyzed by power spectral density analysis techniques (151, 48). Bachrach et al. (3) also indicated that each diver had his own characteristic rhythm or "signature", which has possible applications for monitoring changes in performance and physiology.

Thorne, Findling, and Bachrach obtained amplitude and frequency characteristics of physiological tremor from two subjects during the University of Pennsylvania's Institute for Environmental Medicine simulation dive (equivalent to 1,200 fsw) in 1971, using the NMRI Mark 1 intentional tremor device. When breathing mixtures of helium, neon, nitrogen, and nitrous oxide, the two subjects showed consistent and idiosyncratic differences in tremor signatures independent of gas and depth effects, as had the Makai divers.

Thorne and his co-workers further report that the concurrent battery of performance tasks, consisting of pursuit rotor, grip test, etc., described by Hamilton (71), produced no discernible fatigue or order effects upon low-force physiological tremor. Increasing pressures of helium produced small, consistent increases in tremor amplitudes across all frequencies, while increasing partial pressures of nitrogen produced an increase in the amplitude of low-frequency tremors (0-3 Hz) and a decrease in the amplitude of the normally present 10-Hz peak. Increasing partial pressures of nitrous oxide produced results similar to those for nitrogen, and both were presumed to be "narcosis" effects not directly related to compression tremors. Large and abrupt changes in partial pressures, produced by switching gas mixtures at the same absolute pressure, did not induce "compression tremor." Although the magnitudes were not extreme, several tremor spectra obtained at 1,200 fsw showed atypical peaks or increased amplitudes in the 3-8 Hz range frequently associated with pathological tremors; these amplitudes appeared to be independent of the gas used.

2. Causes of Tremor

Since different types of tremor suggest different neurophysiological events, the proper measurement of tremor requires the accurate description of three factors: (a) the quantifiable physical characteristics (b) the conditions under which tremor was elicited, and (c) the type of tremor reported (i.e., rest, postural, or intentional).

The rate and location of tremors are crucial diagnostic signs. One system of classifying tremors is that developed by Brumlik and Yap (37); their method divides tremors into rest, postural, and intentional tremors, and includes normal (physiologic) and abnormal (pathologic) expressions of these three types. They define the tremors as follows:

Rest is defined as that state in which there is no voluntary innervation of the musculature, i.e., as complete voluntary relaxation as possible. Postural, equivalent to static, refers to that position "when the part is voluntarily held still against the force of gravity, as when the arm is held outstretched". Intentional, synonymous with kinetic and movement tremor, is that seen as the part is moved purposefully toward a goal. The contraction, in contrast to postural tremor, is isotonic, not isometric,* and there is a continual change of tension between antagonistic muscles as the limb is moved through space.

Two theories have been advanced in the past decade to explain normal rest tremor, described as the ballistocardiographic (BCG) and microvibration (MV) hypotheses (37). The BCG hypothesis holds that normal rest tremor is a cardiorespiratory phenomenon, while the MV hypothesis maintains that normal rest tremor arises from the continual contraction of individual muscle fibers. Brumlik (36) states: "The sustained vibration of the entire body mass resonating to the force of blood ejected at cardiac systole is a concept fundamental to the hypothesis." Still another approach is that of Lippold, (98) who sees tremor as a component superimposed upon normal voluntary muscle activity, a "hunting servomechanism" in the reflex arc that controls the muscle.

---

*In actuality, the differentiation between isotonic and isometric is not quite so clear-cut. Most real movements involve an interaction of both types.

All normal tremors--rest, postural, and intentional--tend to show a high-frequency component (between 8-12 Hz). In the abnormal tremor group, abnormal rest tremor (which may be seen in extrapyramidal disease such as Parkinsonism) has a frequency of 3-8 Hz, as does the type of abnormal postural tremor sometimes found in extrapyramidal and cerebellar diseases. In diseases which can involve cerebellar pathways, such as multiple sclerosis, purposeful movement is often accompanied by a 3-8 Hz abnormal intentional tremor. A postural tremor of 8-12 Hz is found in cases of alcoholism and thyrotoxicosis; while the frequency is within the normal range, amplitude may be increased abnormally. Eight-12 Hz is found also in the abnormal postural tremor during shivering, and Lippold, Redfearn, and Vuco (99) report that it may vary from 9-15 Hz. It is thus important to identify the conditions under which tremor appears, the physical characteristics of the tremor, whether the tremor is normal or abnormal, and the body part(s) involved.

In studies of diving tremors, a clear indication of measurement is rarely given. It must be inferred in most cases, as in the 1968 report of Brauer, (25) which noted that the trembling of the hands consisted of rest or postural tremor since no specific or purposeful movement was measured in the limb. Bennett (14) in reference to the 1,500-fsw RNPL dive, described a tremor transducer attached to the middle finger of the right hand from which a frequency analyzer produced an on-line analysis of the tremor over a period of 1 min. This was a postural tremor, measured by having the subject rest his elbow on his knee with his hand extended. EEG frequencies were used for measuring tremor as percentages of change from the surface level. For example, Bennett and Towse (17b) observed a 100% difference between the surface level and 600 fsw tremor recording for one of the divers, which rose to 400% at 1,000 fsw, 600% from 1,100-1,300 fsw, and went down to 275% for 1,400-1,500 fsw.

3. Etiology of Tremors: The Question of Compression Rate

Brauer (25) assumes that high-pressure tremors are substantially different from those changes detected at lower depths and slower rates of compression. In a recent paper, Fructus, Brauer, and Naquet (63) observe that "helium tremors appear to be highly susceptible to compression rate." Although compression rate does seem to be a factor in the appearance of tremor under hyperbaric conditions, its role is far from clear. Bennett (15), has reported the effects of compression to 300 fsw at a rate of 100 ft/min. At these rates on both helium-oxygen and air, no significant changes in EEG or tremor recordings were found. The mixture used was 10/90 oxygen/helium (O_2/He). Bennett further suggests the possibility that the 10% difference in oxygen might have been a factor in comparing this series with earlier ones which used a mix of 20/80 O_2/He and in which some tremor was observed. The question of compression rate with regard to narcosis is also unresolved (6, 12).

Brauer, as noted above, considers pressure to be a more relevant variable than rate, and in a recent report suggests that rapid compression, combined with high pressure, produces marked neurophysiological changes such as convulsion and tremor. In experiments using squirrel monkeys it was found that the higher the compression rate, the lower the atmosphere at which seizures appear. At compressions of 2.5 atmospheres per hour (atm/hr) convulsions did not appear until the pressure was at about 60 ATA, while at 48 atm/hr seizures began at around 50 ATA. Similar findings were reported for tremor. At a 2.5 atm/hr compression rate, tremor appeared at around 30 ATA, while at a compression rate of 24 atm/hr, tremor was observed at less than 20 ATA.

Considering the etiology of tremor from another aspect, MacInnis (105) attributes the lack of tremor in one dive to a number of procedures, including the "reduction of compression temperatures." We have reviewed reports of major deep dives, including chamber, habitat and open-sea, to determine whether tremor and neuromuscular decrement were reported and if so, whether it was actually measured or merely observed.

Owing to the possible relevance of compression rate to tremor, the rate of compression as well as depth are reported where possible. The dives are reported in the matrix, which follows. (Table 12-1).

Figures and other material used in this report have been taken from: W. L. Hunter and P. B. Bennett, "Causes, mechanisms, and prevention of the High Pressure Nervous Syndrome", Undersea Biomed. Res. 1:1-28, 1974; A. M. Bachrach and P. B. Bennett, "Tremor in diving", Aerospace Med. 44:613-623, 1973; and P. B. Bennett and D. H. Elliott, The Physiology and Medicine of Diving and Compressed Air Work. (Baltimore: Williams and Wilkins, 1969.) Where other material has been used, the authors have so indicated.

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975

Dive	Depth/Type of Dive	Time on Bottom	Time/Rate of Compression	Tremor/Neuromuscular Decrement Measured or Observed
Ocean Systems 1965	650 ft chamber	48 hrs 2 min	60 min to depth (10.8 ft/min)	At 20 ft, one S: Tremor at rest observed; difficulty controlling fine hand coordination. Other S: Hand tremors observed during compression beginning at 260 ft.
Royal Navy 1965	600 ft 800 ft chamber	4 hr 4 hr	14 min 33 sec (41.2 ft/min) 8 min 48 sec (91 ft/min)	Neuromuscular decrement measured by manual dexterity (ball bearing) and maze tests; tremor observed.
Royal Navy 1967	300 ft--- 4 divers 400 ft--- 6 divers 500 ft--- 2 divers chamber	1 hr 1 hr 1 hr	3 min 15 sec (92 ft/min) 4 min 54 sec (81 ft/min) 8 min 25 sec (60 ft/min)	Marked neuromuscular decrement measured by a manual dexterity test (ball bearing) and a maze test; mental ability (measured by arithmetic sums) was not significantly impaired.
Westinghouse 1967	600 ft 2 ocean dives Cachalot: divers in DDC* transferred to work site by PTC**	20 min each S	Dive 1: Saturation at 100 ft, then 200 ft/120 min (1.7 ft/min) 250 ft/120 min (0.4 ft/min) 300 ft/120 min (0.4 ft/min)	Decrement in mental ability in arithmetic sums was measured; no tremor observed; decrement in neuromuscular performance was measured by manual dexterity (ball bearing test).

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975. (Cont'd.)

Westinghouse 1967 (Cont'd.)			600 ft at 15 ft/min Dive 2: Saturation at 360 ft, then 5 min to 600 ft.	
COMEX 1968				
Physalis I	33.5 bar 1,050 ft chamber	10 min	113 min	Helium tremors began well before 1,000 ft level with one S.
Physalis II	36.0 bar 1,172 ft chamber	5 min	120 min Surface-31 bar: 80 min 31 bar-36 bar: 40 min	Severe tremors beyond 25 bar; gross motor difficulty beyond 33.0 bar.
Physalis III	36.5 bar 1,189 ft chamber	4 min	123 min 74 min below 31 bar 15 min at/below 36 bar	Helium tremor noted first at 26.0 bar; became increasingly prominent in excess of 33.0 bar. (Psychomotor tests derived from observation and handwriting.)
Physalis IV	977 ft chamber	10 min	180 min	HPNS symptoms: static and kinetic motor signs (static tremor in the attitude of the extremities); kinetic difficulties (saccadic gestures, dysmetria); lowering vigilance level; sudden bursts of theta activity mixed with alpha from the temporo-occipital region.

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975

EDU/Duke 1969	1,000 ft chamber	77 hrs 30 min	24 hrs 22 min 1.5 ft/min	Two divers reported intermittent fine tremors at 1,000 ft while performing tasks requiring precise motor function. One diver reported momentary difficulty with muscular control while lifting. No change in CNS as manifest by either arousal from sleep or in the deep sleep patterns. No tremor reported on cognitive/performance tasks. Some impairment on performance attributed to "psychological stress" related to the hazards of the dive.
Ocean Systems 1969	1,000 ft chamber	6 min (approx)	100 ft/min	Magnetic ring held over induction coil. Minimal tremor recorded.
Makai Range 1970	520 ft habitat	5 days	40 ft/hr (0.67 ft/min)	Normal tremor measured at each atm compression and decompression by muscle force transducer.
Royal Navy 1970	1,500 ft chamber	22 hrs at 600 ft 24 hrs at 1,000 ft 1 hr at 1,100 ft 1 hr at 1,200 ft 22 hrs at 1,300 ft 1 hr at 1,400 ft 10 hrs at 1,500 ft	Surface-600 ft: 16.7 ft/min 600 ft-1,000 ft: 17.4 ft/min 1,000 ft-1,500 ft: staged compression, 16.7 ft/min	Tremor observed and measured by a middle finger transducer; one S showed marked tremors. Tremors worsened immediately after compression and upon morning waking. Performance decrement was in the fine manual dexterity requirements of the ball bearing test and was

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975. (Cont'd.)

Royal Navy 1970 (Cont'd.)				attributed to tremors. Overall depression of cerebral electrical activity was recorded during compression from 1,400 to 1,500 ft.
Royal Navy 1970	1,165 ft chamber	5 hrs	1 hr 10 min to 31 ATA (14.1 ft/min) excursions to 36 ATA	Some tremor observed; also neuromuscular decrement, measured by ball bearing test.
COMEX 1970 Physalis V	1,706 ft chamber	on bottom "a short time" 77 min at 1,700 ft	Surface-1,150 ft: 24 hrs (0-355 ft: 1m/min) At 1,150 ft: 16 hrs; 1,150 ft-1,510 ft: 10 hrs 45 min (1,150 ft-1,310 ft: 1 m/min) At 1,510 ft: 16 hrs 15 min; 1,510 ft-1,700 ft: 7 hrs 23 min (1,510 ft-1,610 ft: 1m/min) At 1,700 ft: 77 min	HPNS symptoms observed: increase in theta waves, in static tremor, kinetic tremors and dysmetry; psychomotor performance measured by inserting and screwing wire into a socket.
Westinghouse 1971	1,000 ft chamber	36 hrs at 450 ft 48 hrs at 650 ft 9 days at 850 ft; 2 bounce dives: 1 hr at 1,000 ft 4 hrs at 1,000 ft	Surface-450 ft: 4 hrs (1.9 ft/min) 450 ft-650 ft: 3 hrs (1.1 ft/min) 650 ft-850 ft: 3 hrs (1.1 ft/min)	Tremor measured by muscle force transducer. Data under analysis.

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975. (Cont'd.)

Univ. of Pennsylvania Inst. Environ. Med. 1971	1,200 ft chamber	4 days at 400 ft 2 days at 700 ft 2 days at 900 ft 6 days at 1,200 ft	Surface-400 ft at 31 ft/min 400 ft-700 ft at 5 ft/min 700 ft-900 ft at 5 ft/min 900 ft-1,200 ft at 2.5 ft/min	Tremor measured by NMRI muscle force transucer. Small but consistent increase in overall magnitude of physiological tremor with increasing depth. No gross "compression" tremors observed. Slight suggestion of reversible pathological tremors which appeared to be independent of breathing mixture used.
COMEX 1971 Sagittaire I	300 m chamber, 4 divers	7 days	11 days 0-252 m: 1m/min stage 48-h at 5, 13, 34, 74, and 152 m. 252-300 m: 0, 17 m/min	Slight tremor appeared between 200-300 m; it persisted in two subjects during the stay at bottom. EEG modifications appeared during the compression between 200-300 m; they persisted during the stay at bottom
COMEX 1972 Sagittaire II	500 m chamber, 2 divers	100 h	49 h Surface-108 m: 1m/min 108-135 m: 0.25m/min 135-238 m: 0.20m/min 238-307 m: 0.17m/min 307-356 m: 0.14m/min 356-392 m: 0.125m/min 392-421 m: 0.111m/min 421-444 m: 0.10m/min 444-462 m: 0.09m/min 462-478 m: 0.08m/min 478-491 m: 0.076m/min 491-500 m: 0.071m/min	HPNS symptoms first appeared in 300-325 m range, increased down to 500 m, condition stabilized after first 40 h with a new increase at the end of the stay at 500 m. Periodic tremor measurements were made (under local EMG and by geophone and computer analysis). Symptoms included static tremor, muscular jerks, lack of coordination, uncertain muscular movements and somewhat marked EEG changes indicating lack of awareness.

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975. (Cont'd.)

COMEX 1972 Physalis VI	2,001 ft chamber	80 min	Surface-1,148 ft: 34 hrs 54 min (0.55 ft/min) At 1,148 ft: 46 hrs; 1,148 ft-1,755 ft: 40 hrs 54 min (0.25 ft/min) At 1,755 ft; 14 hrs 6 min; 1,755 ft-1,854 ft; 10 hrs 6 min (0.16 ft/min) At 1,854 ft: 25 hrs 54 min; 1,854 ft-2,001 ft: 17 hrs 20 min (0.15 ft/min to 0.13 ft/min At 2,001 ft: 80 min	HPNS symptoms at 1,150 ft, disappeared at end of stay at 1,150 ft, more pronounced at 1,750 ft and 1,850 ft "after sleeping at constant depth than during the compression phases."
COMEX 1973 Sagittaire III	300 m chamber, 4 divers	15 days	0-200 m: 2m/min 200-300 m: 1m/min stage: 48 h at 100 m 48 h at 200 m	Tremor appeared about 200 m; it was very slight and persisted during the stay at 300 m EEG modifications appeared between 250-300 m; they persisted during the stay at 300 m.
US Navy/Taylor 1973	1,600 ft chamber, 6 divers	32 days 17 days at depths greater than 1,000 ft ca. 1-day stop at 400 ft ca. 1-day stop at 1,000 ft	0-14 ft: 14 ft/min 14-400 ft: 5 ft/min 400-1,000 ft: 40 ft/hr 1,000-1,300 ft: 30 ft/hr 1,300-1,600 ft: 20 ft/hr	Using NMRI force transducer intentional tremor device, tremor was measured at 400, 1,000, 1,300, and 1,600 ft. Sample: Marked increase in tremor amplitude was measured as well. Marked tremor was observed in and reported by

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975. (Cont'd.)

US Navy/Taylor 1973 (Cont'd.)		ca. 1-day stop at 1,300 ft		divers. Severe disturbance in balance demonstrated by postural equilibrium level.
Duke 1974	1,000 ft	1 hr stage: 1 min at 50, 240 ft; 2 min at 600, 720 ft	Surface-1,000 ft in 27 min	Use of 18% N_2 + He/O_2 (Trimix) suppressed tremors noted when breathing He O_2 alone but nitrogen narcosis present
COMEX 1974 Sagittaire IV	610 m chamber, 2 divers	50 h stages: 17 h at 200 m 46 h at 400 m 45 h at 550 m 45 h at 580 m	10 days and 21 h 0-90 m: 0.17m/min 90-165 m: 0.14m/min 165-240 m: 0.125m/min 240-310 m: 0.110m/min 310-400 m: 0.100m/min 400-550 m: 0.05m/min 550-610 m: 0.166m/min	Very slight tremor appeared about 300 m. It persisted during the stages and the stay on bottom. EEG modifications appeared about 400 m, and were very important after 550 m.
COMEX 1974 Janus III, A	390 m chamber, excursion dives to 415 and 460 m 3 divers	6 days	49 h 0-90 m: 0.17m/min 90-166 m: 0.14m/min 166-240 m: 0.125m/min 240-315 m: 0.110m/min 315-390 m: 0.100m/min	Tremor appeared about 300 m; it persisted during the stay. EEG modifications appeared about 300 m. They were important at 390 m; they decreased during the stay. All the changes disappeared during the decompression between 200 and 100 m.

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975. (Cont'd.)

COMEX 1974 Janus III, B	390 m chamber, excursion dives to 415 m, 3 divers	6 days stages: 1 h at 120 m 17 h at 200 m	49.h 0-120 m: 5m/min 120-200 m: 2m/min 200-240 m: 0.125m/min 240-315 m: 0.111m/min 315-390 m: 0.100m/min	Very slight tremor appeared about 300 m; it disappeared at the end of the stay. EEG changes appeared between 200 and 300 m; they persisted during the stay at bottom.
Duke 1975	1,000 ft	2 hr stages: 1 min at 320 ft; 2 min at 700 ft	Surface-1,000 ft: 33 min. Surface 320 ft: 60 ft/min. 320-700 ft: 40 ft/min. 700-1,000 ft: 20 ft/min	Use of 10% N_2 + He/O_2 (Trimix) suppressed tremors with no narcosis
COMEX 1975 Coraz I	1,000 ft 3 divers	3 days stage: 30 min at 100 m 30 min at 280 m 30 min at 240 m	0-100 m: 4m/min 100-180 m: 2m/min 180-240 m: 2m/min 240-300 m: 1m/min	(With Trimix 9% of N_2) No significant tremor; euphoria at the end of compression and at the beginning of the stay.
COMEX 1975 Coraz II	1,000 ft 2 divers	3 days stage: 30 min at 100 m 30 min at 280 m 30 min at 240 m	0-100 m: 4m/min 100-180 m: 2m/min 180-240 m: 2m/min 240-300 m: 1m/min	Trimix 4.5% N_2 Very slight tremor, slight euphoria at the beginning of the stay at bottom

Table 12-1. Neuromuscular Decrement and Tremor in Reports of Deep Dives 1965-1975. (Cont'd.)

COMEX 1975 Coraz III	1,000 ft 2 divers	2 days stage: 30 min at 100 m 30 min at 180 m 30 min at 240 m	0-100 m: 4m/min 100-180 m: 2m/min 180-240 m: 2m/min 240-300 m: 1m/min	Trimix 6.5% N_2 Very slight tremor, fatigue during the total hours at bottom.

Note that depths and compression rates for COMEX Sagittaire, Janus, and Coraz dives are given in meters or meters/min.

B. EEG Changes and Performance Measurements

From 1968 onward HPNS began to be studied in earnest. By this time some of the early animal studies were available (30) and the COMEX company in Marseilles considered that, with suitable 'slow' compressions, such as 10 ft/min, it should be possible to achieve depths greater than 1000 fsw (31 ATA) without incapacitation due to tremors, or the convulsions reported in animal studies.

In all, seven simulated dives in the 'Physalie' series were made, with two subjects in each dive. Four of these dives exceeded 1100 fsw (34 ATA), and on 27 June 1968, a depth of 1190 fsw (37 ATA) was reached but the dive was aborted after only 4 min. Tremors were observed during compression, the onset occurring at between 725 and 925 fsw (23-29 ATA). Although the compression rate was decreasing, tremors became progressively worse with depth.

Changes in the electroencephalogram (EEG) appeared at depths close to 1000 fsw (31 ATA) and were reported for the first time in man. These were characterized by the appearance of slow waves in the theta band (4-6 Hz) accompanied by depression of alpha activity (8-13 Hz). These changes became worse as the depth became greater than 1060 fsw (33 ATA) and were accompanied by behavioral changes, which included intermittent bouts of somnolence, with sleep stage 1 in the EEG. The subjects woke if aroused, but on resting lapsed again into sleep. The EEG changes persisted for 10-12 hr during the decompression.

These classic signs and symptoms of HPNS were very different from those that could be expected from any narcotic effect of helium. For example, with nitrogen narcosis there are no tremors, marked psychomotor impairment, nausea and vomiting, or similar EEG changes. Indeed, in the latter, the alpha and fast activities are augmented and theta unaffected at 300 ft compressed air (10 ATA) (17c). Further, narcosis does not improve over 1 1/2 hr as does HPNS.

As discussed earlier, the greater the development of the brain, the greater the sensitivity to HPNS. Squirrel monkeys show helium tremors starting at 660-825 fsw (21-26 ATA) and EEG changes, such as spikes, at 1500-1650 fsw (46-51 ATA) which progress to electrical and motor convulsions at some 2050 fsw (63 ATA). Since EEG changes, accompanied by somnolence and tremors, started in man at about 1000 fsw (31 ATA), there was reason to believe that convulsions might have occurred if the duration of the stay at 1190 fsw (37 ATA) had been prolonged, and it was considered that this was the depth limit for practical diving.

Yet a few months later, three Swiss subjects in a joint Swiss/British experiment were exposed to 1000 fsw (31 ATA) for 3 days by compression with helium-oxygen at 16.7 ft/min; they made three excursions, to a depth of 1150 fsw (35.8 ATA) for a period of 2 hr (38). During the excursion, the divers swam underwater using semi-closed apparatus, performed physical work by lifting a 20-kg weight 20 times from floor to full arm extension over the head, and appeared to have no difficulties.

Performance efficiency during both early, briefer dives to 1000 fsw (31 ATA) and the saturation dive did show evidence of tremors (Table 12-2) in the first 1 1/2 hr, as revealed by the ball bearing test, which involves picking up ball bearings with tweezers and placing them in a tube of the same diameter. Other less sensitive tests, however, showed little change, and there was no mental deterioration. Some nausea and vertigo were also reported with the tremor. During the excursions, performance showed no deterioration at all. It was considered, therefore, that HPNS was probably a compression syndrome, consisting of a combination of the heat of compression, psychological stress, and an unknown effect caused by an overfast rate of change of pressure, together with helium hyperventilation.

Urine electrolyte measurements were made under these conditions, as were other measurements of blood morphology and biochemistry. The urine measurements showed a reduction in sodium, calcium, magnesium, and chloride ion, and a diuresis of phosphorus and potassium.

Similar measurements were also made in a dive to 800 fsw (25 ATA) at 3-5 ft/min, with excursions at 27 and 28 ft/min to 1050 (32.7 ATA) and 1100 fsw (34.2 ATA) by International Underwater Contractors Inc. and a U.S. Navy team of scientists from the New London Submarine Medical Center (137, 123). Tremors were observed during the excursions and, as with many such early dives to 1000 fsw (31 ATA) with relatively rapid compressions, arthralgia and aching muscles occurred. Psychological performance was unimpaired.

Urinary pH, CO_2, and bicarbonate increased significantly; in contrast to the Swiss/British dive to 1000 fsw (31 ATA), sodium, potassium, and phosphorus excretion increased, calcium was unchanged, while chloride decreased. These results are believed to be due to hyperventilation resulting in respiratory alkalosis, and certainly this is a common finding in deep oxygen-helium diving. That Buehlmann trained his divers not to hyperventilate at depth may be important, and may account for the different results with the urine electrolytes of his experiments.

1. Measurement of EEG Effects During Compression in Stages

Due to the excellent physical condition of the men in these dives to 1000 fsw (31 ATA) and beyond, it became increasingly difficult to believe that a 'barrier' to deep diving at depths of 1200 fsw (37 ATA) existed. In 1970 an extensive series of dives were made at the Royal Naval Physiological Laboratory (RNPL), culminating in the exposure of two men to a simulated depth of 1500 fsw (46 ATA) for 10 hr. As in decompression, the exposure was made in stages instead of the usual continuous compression (Fig. 12-2).

Table 12-2. Performance Impairment in Deep Saturation Oxygen-Helium and Excursion Dives (Buehlmann et al. 1970).

Tests	Surface	3 days at 31 ATA (1000 ft)							2 hr excursions to 36 ATA
		After compression	1 hr	2 hr	3 hr	24 hr	48 hr	72 hr	
Ball bearing	12±4	6±5	10±6	11±4	12±5	16±6	18±3	17±4	19±4
Dotting	69±12	66±9	63±9	63±7	62±13	61±6	67±6	69±8	63±9
Dotting in squares	38±4	32±4	32±4	34±3	35±5	39±2	36±3	41±2	38±3
Errors %	2	6	3	0	3	6	5	10	9
Letter code	39±6	33±5	30±6	32±4	33±6	38±8	35±4	41±5	37±3
Errors %	0	7	7	2	0	0	0	2	0
Arithmetic correct	9±1	-	11·5±3	-	11±3	14±2	-	14±2	12±2
Arithmetic attempted	9·5±1	-	13·5±2	-	13±3	15±3	-	17±2	14±2

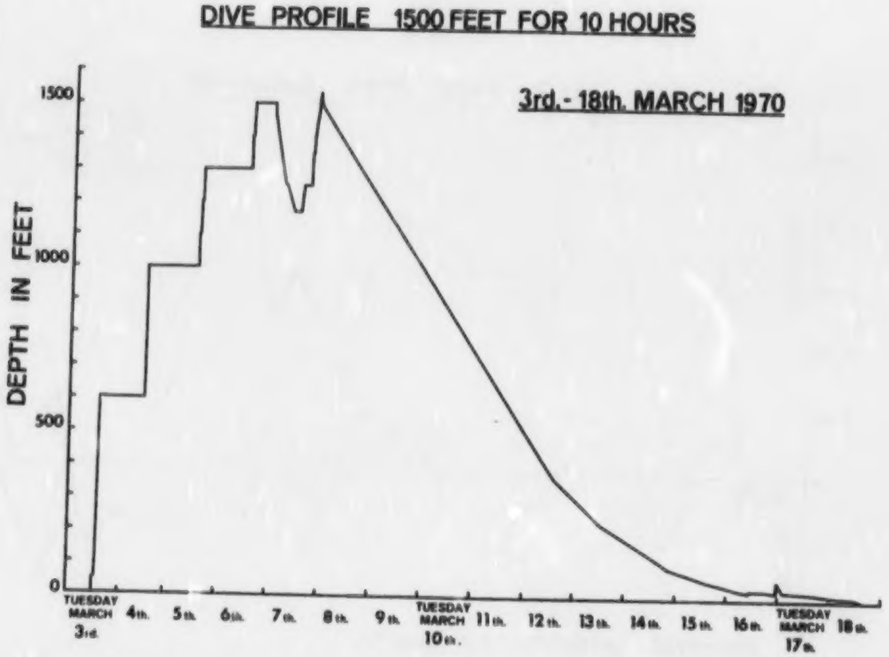


Fig. 12-2. Profile for 1500 ft (46 ATA) simulated oxygen-helium dive at RNPL. The stages on compression are shown together with recompression to 1535 ft (47·1 ATA) during the decompression in order to try to treat vestibular decompression sickness in one of the subjects. At some 30 ft, the other subject required recompression for a mild knee bend (after Bennett et al. 1971).

The first compression was to 600 fsw (19 ATA). After 24 hr the two men were compressed at the same rate of 16.7 ft/min to 1000 fsw (31 ATA), and after a further 24 hr they spent one hour at 1100, 1200, and 1400 fsw (34, 37, and 43 ATA), and a further 24 hr at 1300 fsw (40 ATA). During each stage a vast amount of physiological and medical data was obtained (20, 17a, 18, 114). This dive was the first in which the EEG data was quantified by means of frequency analysis, and sensory-evoked potentials and postural tremors were measured by a transducer attached to the finger, as well as by sensitive psychomotor tests such as the ball bearing test.

As with previous dives, the subjects reported tremors, involuntary muscle jerks and feelings of dizziness with slight nausea, especially immediately on reaching the 600 fsw (19 ATA), and 1000 fsw (31 ATA) stages. The EEG showed a typical increase in theta activity (4 to 6 Hz), accompanied by a reduction of other activities; this reaction was delayed in one of the two subjects to 1300 fsw (40 ATA) (17a). The EEG changes were seen most prominently when the subjects' eyes were open (Fig. 12-3).

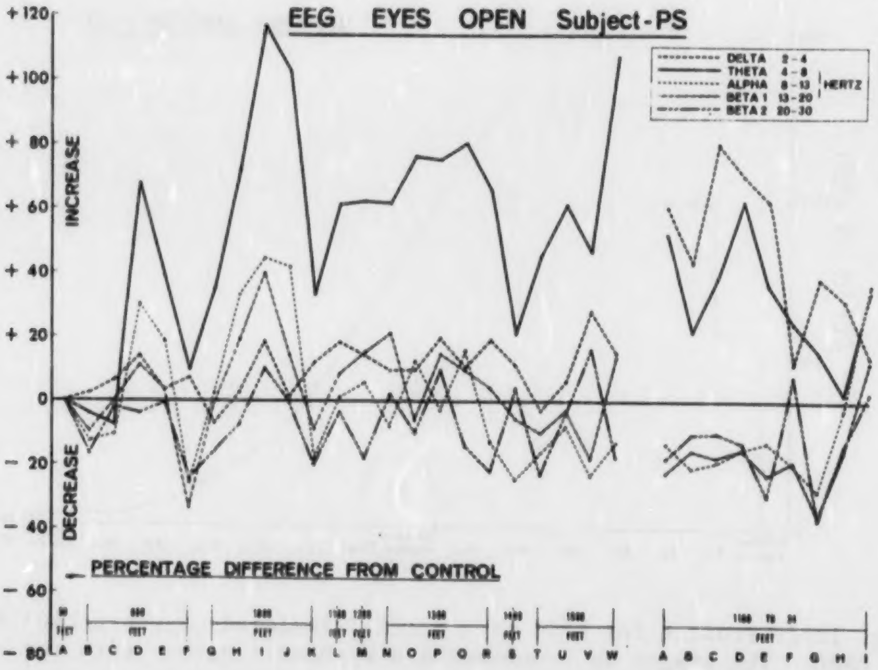


Fig. 12-3. Analysis of one of the two subjects, EEG during the 1500 ft (46 ATA) oxygen-helium dive at the RNPL at various stable stages of the dive as compared to controls at 50 ft (2·5 ATA). A marked rise in theta activity is indicated, initiated by each stage of compression. This continues to increase for 6 hours and then returns to lower levels over 12 hours (after Bennett & Towse 1971a).

Each compression phase stimulated an increase in theta activity, and this activity continued to increase for 6 hr after compression had ceased and then returned to nearer normal levels over a period of about 12 hr. The cortical auditory-evoked potentials showed a progressive depression with increasing depth which was at its most significant from 1300-1500 fsw (40-46 ATA), when the size of the N_1P_2 complex showed values 30-50% less than controls. These results showed that there are two aspects of EEG change in the brain during HPNS in man: a rise in theta activity associated with compression, and depression of overall electrical activity, which is a function of increasing depth. Compression phenomena have a cycle of growth and decay of about 20 hr, but the depression of overall activity shows no improvement with time and becomes progressively worse with increasing depth (17).

It is pertinent that Zaltsman (156) also reported EEG changes with oxygen-helium compressions of 30-60 ft/min and compared the results with exposure to nitrogen at 70-350 fsw (3-12 ATA), and argon at 30-200 fsw (2-7 ATA). Lessening of amplitude and an increase in frequency of alpha was reported. With nitrogen and argon, this was followed by intensification of fast activity on a background of suppressed alpha until eventually theta activity took its place. No slow activity was seen at 630 fsw (20 ATA) with helium in spite of other quite marked signs of HPNS, such as impairment of mental efficiency, memory, motor reflexes, and changes in the dimensions of writing. There is little doubt, however, that changes would have been observed with the use of frequency analyses.

The tests of performance decrement during the 1500 fsw (48 ATA) exposure correlated with the degree of tremor present (Fig. 12-4), but there was no mental deterioration.

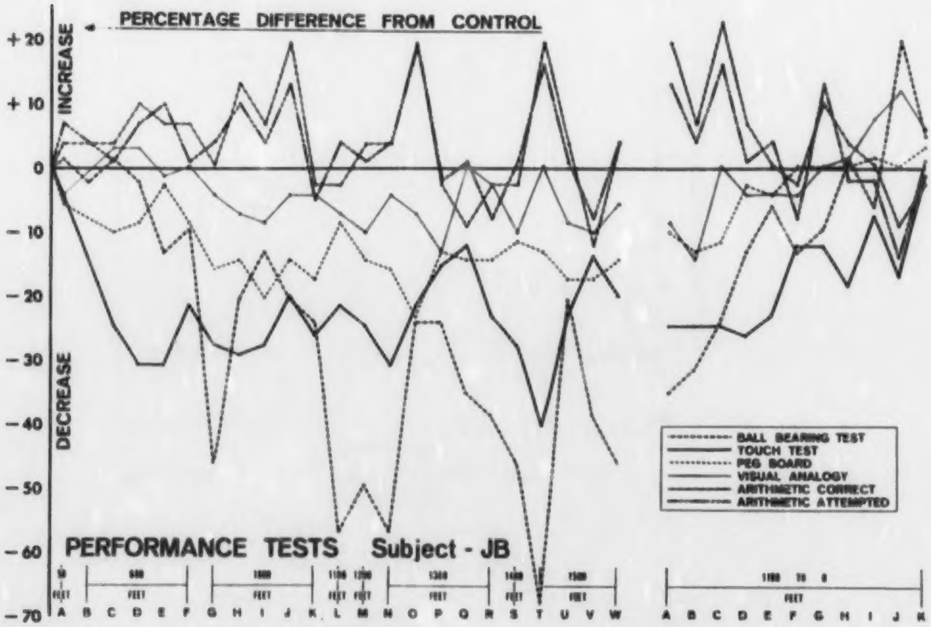


Fig. 12-4. Changes in performance tests compared with surface controls during 1500 ft (46 ATA) oxygen-helium exposure. Intellectual performance is unaffected but psychomotor tests indicate an increasingly greater decrement with the sensitivity of the test. The decrement correlates with the onset of tremors elicited by each compression phase (after Bennett & Towse 1971b).

This supported earlier hypotheses that helium would not have narcotic properties (39, 19). A transducer on the middle finger permitted measurement of the degree of postural tremor, its interindividual variations, and its association with too fast a rate of compression; in addition, a more permanent tremor which became worse with increasing pressure was apparent (Fig. 12-5).

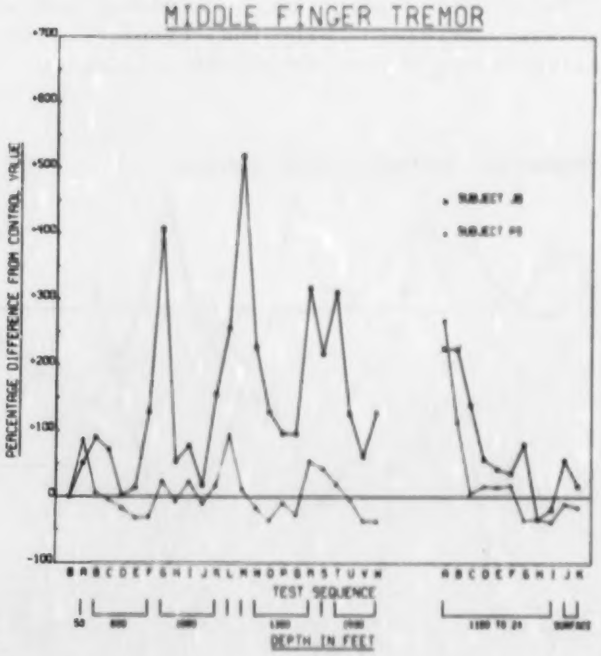


Fig. 12-5. Postural tremor measured from an accelerometer on the middle finger during a 1500 ft oxygen-helium simulated dive. Each compression phase elicits an increase in tremor which is more marked in one subject than the other. In the latter there is also a progressive increase in base-line tremor with increasing depth (after Bennett & Towse 1971b).

C. The COMEX Exploratory Dives

In November 1970, the COMEX company undertook another dive, called Physalie V, using a similar dive profile, with stages, an increasingly slower rate of compression, and three fast phases of 1 m/min between 0-355, 1150-1310, and 1510-1610 fsw (0-11.7, 35.7-40.6, 46.7-49.7 ATA) to attain 1706 fsw (52.5 ATA) for a short time. Despite these precautions, HPNS occurred, but its effects were considerably less severe than in the earlier (1968) experiment. However, frequency analysis of the EEG showed the usual compression-related increase in theta activity and reduction of fast alpha and beta frequencies (Fig. 12-6).

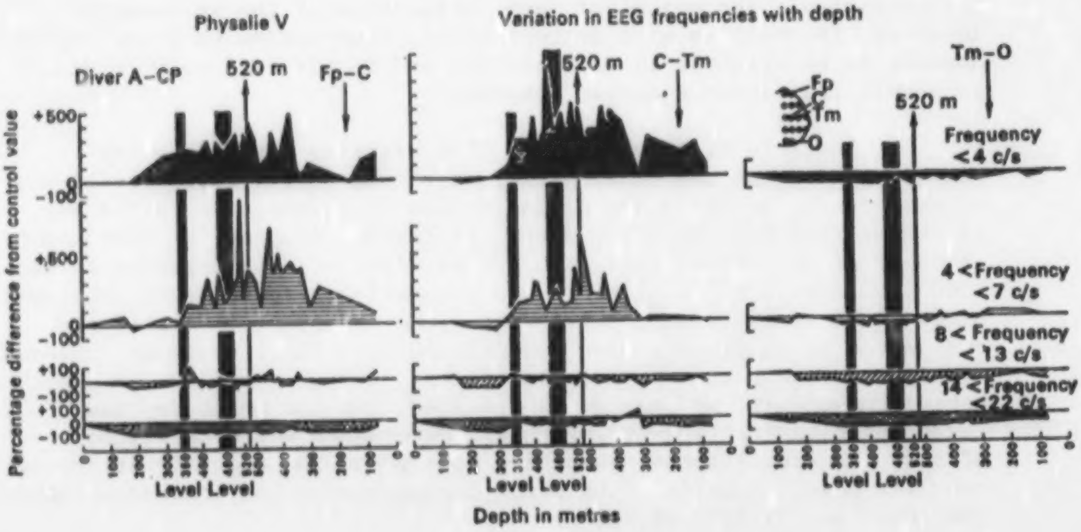


Fig. 12-6. Frequency analysis of the EEG showing the rise in theta (4 to 7 Hz) and delta (less than 4 Hz) and depression of alpha (8 to 13 Hz) and beta (14 to 22 Hz) frequencies together with variations due to different electrode placement in the COMEX dive to 1706 ft (52·5 ATA) (after Fructus 1972).

Tremor appeared at between 1000 and 1150 fsw (31-40.6 ATA), became marked after 1600 fsw (49.5 ATA), and occurred in two forms: static, presumably postural, and kinetic and dysmetric, presumably intentional. There was also a drop in awareness in moments of relaxation and performance tests showed reduced efficiency (62, 61, 132).

The improvement noted in Physalie V compared with the earlier French dives was attributed to having taken the effects of osmotic dybarism into consideration during the dive. (The possible role of such an osmosis is discussed later in this report in the section on etiology).

Similarly, Chouteau, Ocana de Sentuary, and Pironti (41a) formulated a relationship also based on the osmotic theory which assumes that dissolved inert gas tension within a tissue of given half-time is not in equilibrium with the inspired inert gas partial pressure during compression and should not exceed a certain Δp which was about 10 bar. However, this theory exhibits anomalies as well as agreements (17c).

There have been many attempts to fit mathematical models to the data of compression and decompression theory, but all such attempts to calculate profiles are hampered by an inadequate knowledge of the causes of the mechanisms involved in compression and decompression. The one clear fact, regardless of the mathematics involved, is that, as with decompression, compression to great depths appears to be essentially exponential, and should be done with stages to permit adaptation whenever possible.

The role of adaptation to HPNS was also studied by the COMEX organization and CNEXO (Centre National pour l'Exploitation des Oceans) during a dive known as Sagittaire II. This dive lasted for 100 hr at 1640 fsw (51 ATA), with a decreasing compression rate ending at 14 ft/hr on arrival (61). The first signs of HPNS appeared in the 1000-1200 fsw (31-37 ATA) range and gradually increased with compression. After 40 hr at 1640 fsw (51 ATA) the signs and symptoms stabilized and showed no adaptation over the next 60 hr. These symptoms included static (postural) tremor, muscular jerks, lack of coordination of certain movements, and marked EEG changes, some of which denoted a lessening of awareness. Psychomotor performance was only slightly affected and intellectual faculties were good. No significant improvement was observed until 40 hr after decompression had started at about the 1000 fsw (31 ATA) depth.

In June 1972, the deepest dive to date, called Physalie VI, was made by the same French group. It culminated in the exposure of two men to 2001 fsw (60.5 ATA) for 80 min. The equivalent density of the Physalie VI breathing mixture compared to air would be found at 266 fsw (8 ATA), and the compression rate again involved a slower and slower compression with stages (Fig. 12-7).

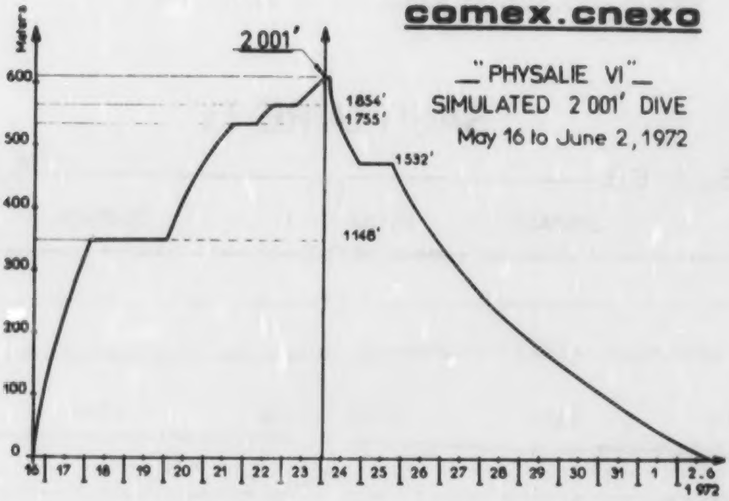


Fig. 12-7. Dive profile for the simulated deep dive to 2001 ft (60·5 ATA) in June 1972 by COMEX (after Fructus and Charpy 1972).

HPNS appeared at 1150 fsw (35.7 ATA) and was more marked on arousal from sleep during the 1750-1850 fsw stage (54-57 ATA) than during compression. Performance efficiency varied with the individual, one showing a decrement of 18-48% depending on the test, with a 20% decrement in manual dexterity, the other showing only a 16% decrement in manual dexterity. Both subjects showed an increase in reaction time (59a). The effects seen were considered to be less than those in the 1500 fsw (46 ATA) British dive, and they bode well for the success of operational diving to 1500-1600 fsw (46-49 ATA). Clearly, from the progress indicated by these dives, slower compression is a significant advantage in attaining deeper depths.

In 1974, the French group made a further dive (Sagittaire IV) to a depth of 610 m. The compression curve was interrupted by a primary stage of 17 hr at 200 m, another of 45 hr at 400 m, and two further stages lasting 46 hr at 550 and 580 m. Speed decreased in relation to depth down to 400 m, was held constant at 3 m/hr between 400-550 m, and at 10 m/hr between 550-610 m. The total time for the Sagittaire IV dive was 261 hr. The two divers stayed at the bottom for 50 hr and decompression was accomplished over 231 hr. Sagittaire IV was undertaken to study: 1) the effects on HPNS of a compression rate slower than that of Physalie VI (0-550 m/hr); 2) the effects of fast compression at great depths (between 550-610 m).

During Sagittaire IV, postural tremor appeared at about 300 m, but the intensity of the tremor was less than that observed in the preceding COMEX dives between 500-610 m. However, tremor did not decrease during the different stages nor during the stay on the bottom.

EEG modifications appeared at about 400 m (Fig. 12-8),

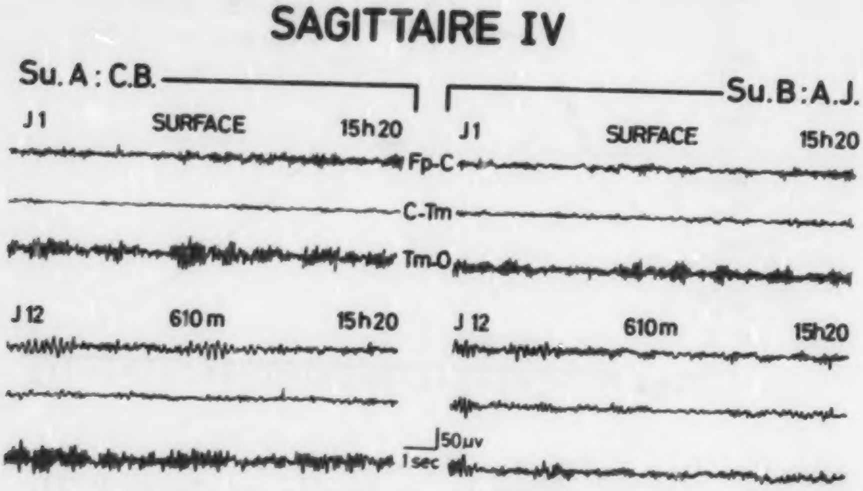


Fig. 12-8. EEG trace, with eyes closed, for 2 subjects of Sagittaire IV dive. Left: subject A, C.B.; Right: subject B, A.J. From top to bottom: surface to 610 m. For each subject the following regions are shown: Fp-C, fronto-polar-central; C-Tm, central-mid temporal; Tm-O: mid temporal-occipital.

and became significant between 550-610 m despite stages of 45 hr at 550 and 580 m. Evidently, the speed of 10 m/hr canceled out the "stabilizing effects" of the various stages of long duration (133). However, at 610 m the decrement in manual performance was slight (20%), but the decrement in intellectual performance was more important (40-50%).

Over the period of its research, the COMEX group has made 12 dives to depths between 300-610 m to study the effects of HPNS. Twenty-four subjects were involved in these dives; some of the subjects made two dives. In general, the French dives can be classified as follows: Physalie I to Physalie VI: exploration dives using 2 subjects, with a short stay at bottom; Sagittaire I to Sagittaire IV: saturation dives using 4 subjects (Sagittaire I and III), and 2 subjects (Sagittaire II and IV); Janus III, A and B: working dives using 3 subjects.

Each of the COMEX series had different profiles, especially for compression rates: Physalie I, II, and III: rapid compression;

Physalie IV, Sagittaire I and III: rapid compression interrupted by stages at intermediate depths; Sagittaire II and Janus III, A: slow compression at decreasing rate; Physalie V and VI, Sagittaire IV, and Janus III, B: slow compression at decreasing rate interrupted by stages at intermediate depths (see Table 12-1).

The elevated PpO_2 during the first dives (500-600 mb, Physalie I and IV) was lowered to 400 mb during later dives. Temperature varied between 31-33 °C, according to depth. Humidity, elevated during the first dives (70%), was maintained between 40-60% during later dives. Throughout the COMEX dives, subjects underwent a series of tests to study the clinical and electrophysiologic symptoms of HPNS. Table 12-3 shows the number of observations carried out at various depths.

Table 12-3. Number of Times Men have Reached 300 Meters Depth and More (COMEX). (24 Subjects)

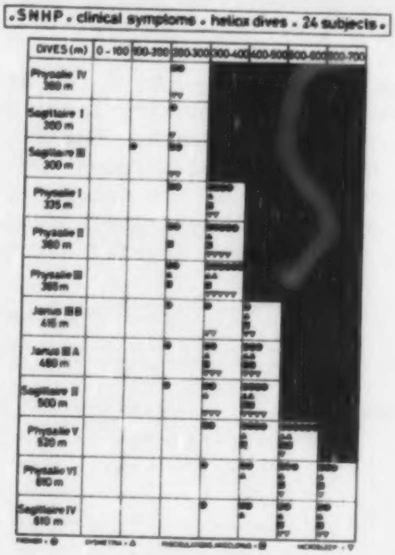
300 meters .... = 30
335 " .... = 20
360 " .... = 18
365 " .... = 16
415 " .... = 16
460 " .... = 14
500 " .... = 11
520 " .... = 8
610 " .... = 6

1. Clinical Signs Observed by the COMEX Group

The French group has characterized the clinical signs of HPNS as tremor, dysmetria, fasciculation, myoclonus, and drowsiness (microsleep). Major EEG modifications are augmentation of theta waves (slow activity), diminution of alpha waves (fast activity), and microsleep. There are also disturbances in the organization of sleep. The group did not notice any disorganization, nausea, or dizziness, symptoms which are probably dependent on compression rate (132, 117).

The COMEX group concluded that the degree of tremor is a function of compression rate. For example, during Physalie V, using rapid compression between 350-400 and 460-490 m, tremor reached a level 700% above normal between 490-520 m, while during Physalie VI, with compression to 610 m, tremor did not rise more than 250% above normal. Tremor persisted so long as the subjects stayed at constant depths, and remained notable even when 100 hr were spent at 500 m. It disappeared during decompression, more rapidly if it was not serious at bottom depth. Table 12-4 recapitulates the clinical signs of HPNS observed during the COMEX dives.

Table 12-4. Clinical Signs of HPNS. Tremor, Dysmetria, Fasciculations, Myoclonic Jerking, and Drowsiness.



Dysmetria was detected with classical neurological tests, and appeared to be inconstant and more or less visible from subject to subject. It can appear as early as 300 m during rapid compression, but was generally observed below 400 m, and disappeared during decompression.

Fasciculations and myoclonia are superimposed on the tremor when it reaches high intensity. Fasciculations generally appear before myoclonia; both occur predominately in the upper limbs, and sometimes in the face and neck muscles at high pressures. Onset of these symptoms occurs between 200-300 m during rapid compressions, and below 500 m for slow compressions. They regress slightly during prolonged stays at constant depths, and disappear at the same depths during decompression at which they appeared during compression.

Drowsiness appeared in some subjects left at rest, but did not appear systematically in every subject. It was less constant and affected fewer subjects during slow compressions with intermediate stages. Drowsiness persisted during extended stays at bottom depth, and usually disappeared in the 200-m decompression zone, though it continued in some subjects until after they had left the pressure chamber.

Other symptoms observed by the French group were nasal congestion, which occurred below 400 m whether the humidity was above or below 70%, and a lighter phase of sleep, with vivid dreams or nightmares.

2. COMEX Conclusions

The clinical signs of HPNS observed during the COMEX dives have led Fructus and Rostain to conclude that: 1) The effect of mode and rate of compression on the appearance and intensity of diverse neurological disturbances is irrefutable. 2) The intervention of other hyperbaric effects is apparently responsible for the persistence of certain neurologic symptoms (tremor and drowsiness) during prolonged stays at constant depths. Pressure itself, or perhaps breathing gas mixtures at high pressures, may play a role in the persistence of these signs. Both of these have been postulated by different authors as a result of experiments using men and animals (41, 111, 32, 17d, 130). 3) The nervous origin and mechanisms of these disturbances are still unknown; it is therefore imperative to use slow compression with stages at intermediate depths to ensure that divers involved in dives between 300-610 m arrive at the bottom in a physiologically acceptable state.

IV. ASPECTS OF HPNS IN ANIMALS

The role of animal experimentation in the development of current knowledge of HPNS is a dual one: a) many of the critical questions concerning the health and safety of human subjects exposed to HPNS have evolved from the extensive body of descriptive material collected in animal studies; and b) animal studies have allowed experimenters to manipulate HPNS in an attempt to understand its etiology, and to develop concepts which will eventually allow HPNS to be controlled in human diving operations.

A. History of Animal Research

The story of the recognition of pressure as the basic etiologic factor underlying the nervous system changes, now known as HPNS, provides an excellent example of the importance of animal research. By the late 1950s, diving physiologists had made great strides toward understanding and managing some of the principal hazards which beset divers in their progress toward the depths. Oxygen toxicity, the narcotic effects of inert gases used as oxygen diluents in high-pressure environments, the mechanical effects of dense atmospheres upon respiratory work, and the effectiveness of ventilation held the attention of investigators to such an extent that, when the first indications of the effects of high pressures upon the central nervous system of higher vertebrates were encountered in the course of animal experiments at the Sechenov Institute in Leningrad and in human experimental dives at the RNPL in England, these effects were attributed to 'helium narcosis', and were referred to as 'potentiation of the convulsant effects of oxygen by helium' (153) or as 'helium tremors' (13). Recognition that high pressure itself could pose a problem in diving first occurred as a by-product of independent studies of inert gas narcosis in two laboratories. One study revealed the role of the reversal of narcosis by high hydrostatic pressures (112); in another series of experiments dealing with the narcotic potency of helium and hydrogen, high-pressure convulsions occurred as an unexpected complication (27).

In fact, these observations merely continued a chain of studies begun in the late 1880's by Regnard (127), who first studied the effects of high hydrostatic pressures upon a variety of organisms, and clearly described the now familiar sequence of hyperactivity, spasms (subsequently often mis-named tetany), and paralysis at progressively increasing pressures. Regnard's early descriptive work was heavily conditioned by technical difficulties which limited the studies to changes that persisted after decompression. His work was followed by the studies of Fontaine (58) and Ebbecke and his associates (49, 50, 51) who focused their attention upon the physiology of muscles under pressure. Later, D. Brown, Johnson, Eyring and their associates (82) studied the effect of pressure on simple and complex enzyme reaction chains. More recently, the work on cell biology and especially on cell division processes initiated in the USA by Marsland (106) has been the center of attention. Zimmerman (157, 92, 84) and Landau, and Kitching and his students in the United Kingdom, have continued with this work.

Curiously, throughout this long period of more than half a century, little attention was paid to the central nervous system. Fontaine (1930) felt that the excitement phase of the pressure syndrome depended largely on the presence of a central nervous system. A few investigators examined nerve fibers or nerve muscle preparations. Among these, Ebbecke and Schaefer (51) noted that the direct excitability of frog gastrocnemius is always reduced by compression, while Grundfest noticed that occasional nerve muscle preparations stimulated by the nerve showed a lowering of threshold voltage resulting in lowered excitability at pressures around 100-200 ATS (68). Grundfest and Cattell (69) working with single nerve fibers in paraffin oil, recorded repetitive after-discharges, increased spike potentials, and spike duration at 300-500 ATA, and noted the marked enhancement of the negative after-potential at pressures as low as 35 ATA. In squid giant axon, threshold stimulation currents were appreciably reduced at 100 ATA, and the duration of membrane impedance change was increased 50-100% at 200 ATA. At 200-500 ATA, these fibers fired spontaneously (143). The narcotizing effect of ethanol upon this preparation could be reversed at 500 ATA. Finally, Gershfeld and Shanes (65) demonstrated that at pressures of 150 ATA or greater, toad sciatic nerve showed an increased sodium ion content and loss of potassium ion which resembled the action of veratrine. Unlike the veratrine effect, however, this partial depolarization was not reversed by cocaine. More recent (and as yet largely unpublished) work has not fully sustained the impression gained from these early reports. Intracellular measurements of axonal potentials (Henderson, unpublished observations), isolated crustacean nerves and ganglia (Campend, unpublished data) and studies on rat diaphragm nerve muscle preparations (Kendig, unpublished observations) all suggest that conduction is slowed and excitability depressed at high pressures. Clearly, while further work in this direction is needed, the data raise the possibility that HPNS hyperexcitability may prove to be a function of more complex organization, rather than of changes in function at the cellular level.

By the mid-1960s, knowledge of high pressure effects on other biological systems had made considerable progress, both on the theoretical and on the descriptive levels. Thus a reviewer could confidently say in 1970 that 'it is not so much the presence of high pressure effects in vertebrates subjected to 50 or more atmospheres that needs explaining, as the observation that effects are so relatively modest and specific' (157).

B. Description of HPNS in Animals

To date the entire sequence of HPNS stages has only been seen in animal experiments; data from this source warned experimenters that the seemingly trivial early signs of HPNS in man had ominous import.

Development of HPNS has been followed in some detail in numerous species: Rostain et al. (134) have described it for the baboon; Lever et al. (96) used mice and newts; Albano and his co-workers (1) studied rats; and Brauer and his co-workers have done research with mice (30), squirrel monkeys (28), and 20 other vertebrate species (32). Zaltsman et al. (156) and Zaltsman, Selivra and Ponomaryer (155) encountered events now clearly recognizable as stages of HPNS in dogs and in mice. On the basis of this extensive material it is now possible to construct a generalized description of the stages of development of HPNS in the higher vertebrates.

C. Stages of HPNS Development in Animals

The first stage of the syndrome consists of motor disturbances, which tend to be expressed in the form of enchanced, somewhat irregular motor activity in the lower vertebrates, but which are seen as tremors or as somewhat jerky movements of the head or extremities in mammals and birds. Measurements of the frequency of tremors in both men and baboons have been reported (Fig. 12-9).

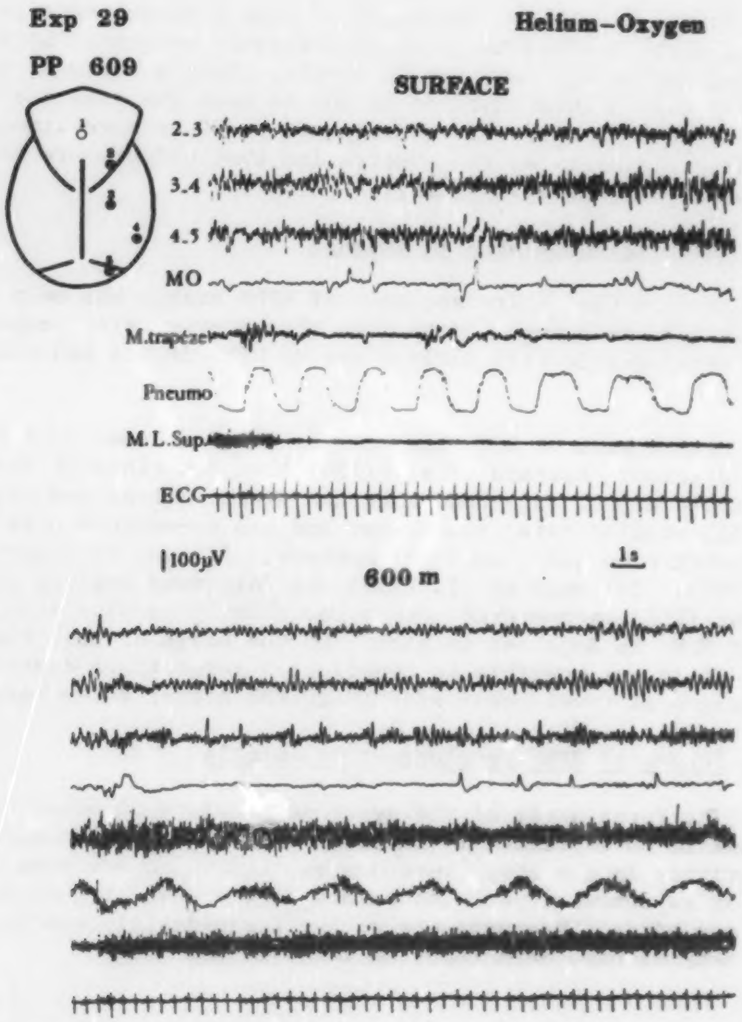


Fig. 12-9. Baboon 609. 1st 3 tracings from EEG leads as indicated. 4: Eye movement; 5: Trapezius; 6: Pneumogram; 7: Supinator; 8: ECG. Note onset of EEG slow wave changes (600 m), and rhythmic tremor (10-12 Hz) in myo- and pneumograms.

It is interesting to note that the dominant frequencies of HPNS tremors in baboons fall in the range of 8-12 Hz and thus closely reproduce the tremors described for human subjects (130). This stage is succeeded in mammals by a second stage of isolated non-volitional myoclonic jerks, again most often noticeable in the face and upper extremities. These symptoms increase in severity and spread to include all parts of the body until the third stage occurs, marked by generalized clonic or tonic-clonic convulsions. If pressure is maintained constant at this stage while the tremors persist, several additional seizures occur at increasing intervals. Further increasing the pressure eventually produces prolonged tonic seizures in the majority of animals. If, on the other hand, pressure is reduced after the first seizure, the convulsions subside promptly. If the convulsive phase of the syndrome is suppressed pharmacologically, a fourth stage will eventually develop, the physiological nature of which has not been fully studied. There is some reason to suspect that this stage may represent the effect of hydrostatic pressure on contractile tissues, and that the inactivity and eventual death that characterize it may reflect cardiorespiratory failure (112).

The first three stages of HPNS development are of practical importance. Comparative studies of numerous vertebrate species suggest a definite and common pattern for the relation between pressure attained and the stage of HPNS reached. This is illustrated in Fig. 12-10 which

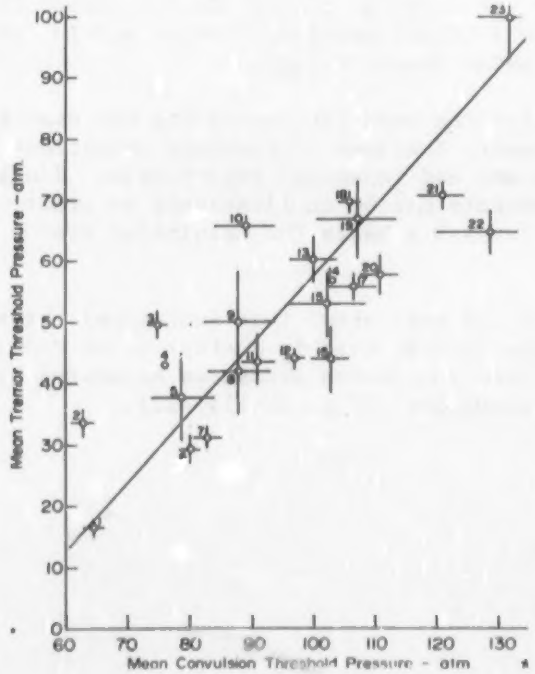


Fig. 12-10. Correlation between mean HPNS tremor and convulsion thresholds for 22 vertebrate species, with least square regression line; r = 0.83; bars = SD for PC and PT for each species.

shows the relation between the mean pressures at which stage I tremors begin and the mean convulsion-threshold pressures (stage III) observed in 22 vertebrate species subjected to compression in helium-oxygen atmospheres, under one particular set of compression conditions (T=31-33 °C, P=24 ATA/hr, PO_2=0.4-0.5 ATA). The data can best be described by a simple equation:

$$\overline{PC} = 49.6 + 0.89\ \overline{PT}$$

where $\overline{PT}$ and $\overline{PC}$ are the mean tremor and the mean convulsion-threshold pressures, respectively (32). Since tremor thresholds for man under these compression conditions are known (PT is about 26 ATA; (34)), this equation allows a reasonably informed prediction of the convulsion threshold for human subjects compressed under the particular conditions of this study (helium-oxygen atmosphere, PO_2 = 0.4 ATA; compression rate, P = 24 ATA/hr; chamber temperature, 31-33 °C). The most likely mean convulsion threshold for man under these same conditions is 65 ± 8 ATA a value that is in good agreement with the data on baboons, which developed tremors at a mean of 36 ATA and convulsions between 65 and 70 ATA (131c, 130).

D. Individual Variations in Animals

Within any given species, development of HPNS is subject to a considerable degree of individual variation. Statistical analysis shows that the variance is of the order of ± 5-10 ATA for either PC or PT, in groups as diverse as a lizard species, a mouse strain, or squirrel monkeys from the Peruvian Amazonia (32).

These results emphasize the need for respecting the statistical character of any experiments designed to quantify conditions affecting HPNS development in man and in animal experiments. Single observations on one or two subjects may be qualitatively of great significance, but can hardly furnish a basis for meaningful prediction of effects.

On the other hand, it has been shown that individual thresholds for convulsions and other signs of HPNS tend in monkeys to be replicated closely for the same subject over successive exposures separated by 4 or more months of 'rest and recreation' (Fig. 12-11) (32).

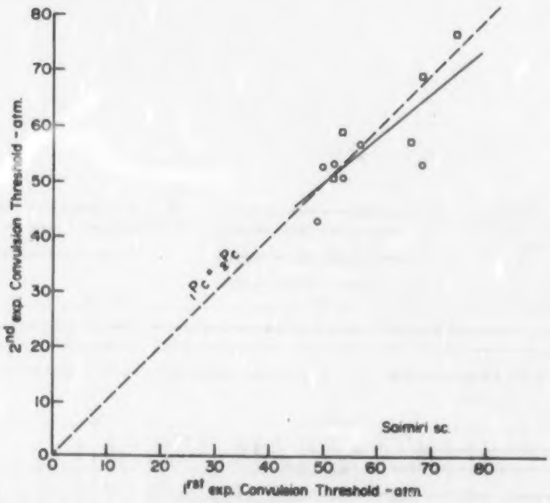


Fig. 12-11. Relation between convulsion thresholds of male squirrel monkeys in two successive exposures to high pressure heliox atmospheres, separated by 4 months' recovery. The solid line represents the computed least square regression equation $_2PC = 8.8 + 0.83\ _1PC$. Circles represent bounce dives; squares represent saturation dives.

The average difference in convulsion thresholds between the first and second exposure was only in the range 1.25-1.50 ATA. There is thus strong evidence that HPNS convulsion thresholds are a stable individual characteristic, and therefore that the selection of individuals for high HPNS resistance should prove possible.

E. Electrophysiological Effects in Animals

The motor events described are the most readily noticed, but constitute by no means the only manifestations of HPNS. In addition, there are electrophysiological, probably autonomic, and perhaps cognitive, changes which accompany the several stages of development of HPNS.

Electroencephalographic changes accompanying compression in heliox atmospheres have been described for the baboon (131c), for the rat (1, 17), for the dog (156, 155), and for the squirrel monkey (28, 79).

During stage I in the squirrel monkey (30-40 ATA at P = 24 ATA/hr), bilateral slowing to the theta range was noted, associated with visible tremors (79). In the baboon (Fig. 12-12) Rostain (130) reported no EEG changes at comparable compression rates below 60 ATA, while tremor onset was noted between 30-45 ATA.

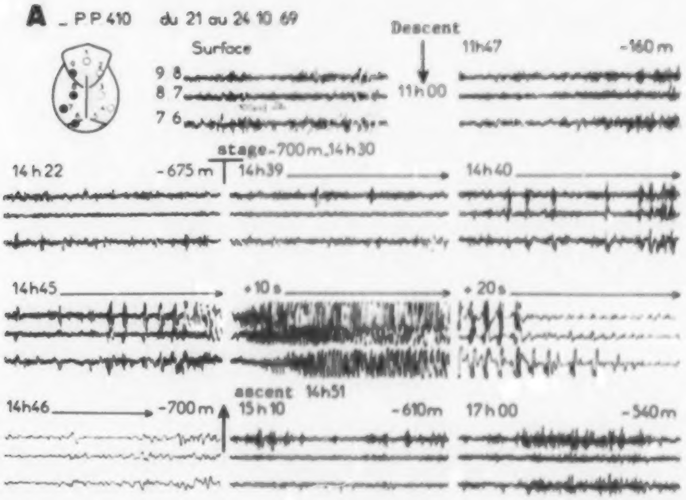


Fig. 12-12. EEG tracings of baboon 410 (leads indicated at upper left) during simulated dive in heliox to 700 m. Note appearance of isolated spike at polyspike complexes in frontal cortex at 700 m, followed after 6 min by grand mal type seizure. Return to normal tracing between 600 m and 540 m during decompression.

In the rat, Albano and his co-workers (1) observed the appearance of slow wave activity associated with voluntary movements at about the time of the appearance of tremors. They noted that these changes disappeared rapidly if compression was stopped and the animals maintained for some time at constant pressure. Bennett and Dossett (17) also confirmed this trend in the rat by using a Nihon Kohden frequency analyzer which revealed the increased relative importance of theta and especially of delta waves in what appear to be stage I animals. The slow wave activity effect disappeared in Bennett's experiments when compression rates were slowed from 200 to 20 ATA/hr. This was followed by a general reduction in amplitude somewhat less marked in the delta than in the alpha range. This result now appears to be due to hypothermia (43). These results differ slightly from those of other observers, due to the high PO_2 of 2 ATA which was utilized throughout, and Bennett and Dossett have speculated about the possible contribution of the narcotic effects of oxygen to their findings.

In dogs, Zaltsman (153) reported increased theta wave activity at pressures which appear to represent stage I HPNS in that species.

Stage II of HPNS in the baboon (130) and the squirrel monkey (28, 79) is associated with the appearance of multifocal spiking and sharp waves, especially over the frontal rolandic areas in the baboon (130), and occasionally also over the occipital regions in both primates. As pressures are raised further, these changes become more prominent and tend to spread, along with greatly increased non-volitional, often myoclonic, motor activity. Similar changes are reported by Albano and his co-workers (1) for the rat, but are absent from the animals exposed in heliox at PO_2 of 2 ATA by Bennett and Dossett (17).

Stage III is associated in all species with paroxysmal EEG crises of the polyspike or spike-and-wave type. Crises of this type may develop either by generalization from isolated areas of focal activity, or they may appear abruptly upon a nearly normal EEG background; they tend to involve the entire cortex, but may at times remain partly confined to a region such as the right or left occipital cortex (130, 79).

Post-ictal periods of coma and EEG flattening lasting from 15-30 sec generally follow such seizures, and are followed by a return to more normal EEG activity and clinical behavior. If compression is continued after the first seizure, additional seizures will occur and the EEG will tend to become increasingly disorganized. Eventually, any periods of normal activity virtually disappear, and the EEG may consist of a nearly continuous series of seizures.

F. Absence of Generalized Autonomic Effects in Animals

Development of HPNS is not accompanied by a generalized autonomic discharge. Thus, the heart rates of squirrel monkeys (28) and baboons (130) remain virtually unchanged, or increase only very slightly, until the moment of a generalized convulsive motor activity. Similarly, respiratory rates remain constant in many cases until the motor seizure is well developed. A perceptible hyperpnea has been recorded in rats beginning about the time of onset of tremors, (1) and supposedly secondarily to enhanced motor tone. Whether more subtle changes in blood pressure or in regional blood flow occur remains unknown and constitutes another area where further experimental work is required.

G. Temperature Regulation in Animals

In the squirrel monkey, rectal temperatures drop during the early stages of compression, when air is replaced by helium-oxygen at 30 to 33 °C, but they remain approximately constant throughout the remainder of the compression until the advent of the generalized convulsions of stage III. In the baboon, cerebral and rectal temperatures likewise fall during stages I and II (by about 2 °C), but they may occasionally show a distinct rise just before onset of convulsions (130). In mice, the severe thermal conditions of the high pressure heliox environment result in a marked decrease in rectal temperature and a similarly marked increase in metabolic rate (Fig. 12-13), which persist through the onset of the severe tremors of stage II (140).

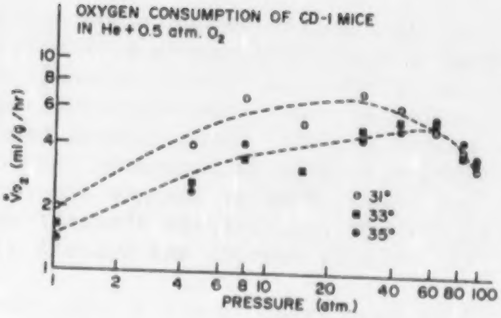


Fig. 12-13. Effect of temperature and pressure on oxygen consumption in resting CD-1 female mice in helium + 0.5 ATA O_2. Values are shown at three temperatures: 31 °C (open circles), 33 °C (filled squares), and 35 °C (filled circles), and at nine pressures: 2.0 ATA, 4.4 ATA, 7.8 ATA, 14.6 ATA, 28.2 ATA, 41.8 ATA, 62.3 ATA, 82.6 ATA and 96.2 ATA. Mean O_2 consumption values are expressed as ml O_2/g body weight/hour.

Beyond this point the metabolic rate ceases to increase with further compression, and evidence for the existence of a lower critical temperature disappears. This raises the possibility that the metabolic response to thermal challenge may have been impaired; this could be attributed to pressure-induced changes in hypothalamic function or to the availability of central neurotransmitters involved in thermo-regulation (54).

In the lizard *Anolis carolinensis*, development of HPNS is often accompanied by progressive melanophore expansion, leading to changes in skin color from green toward brown—a kind of colorimetric index of the stages of HPNS development (Brauer and Venters, unpublished data). This color change reflects the degree of expansion or contraction of chromatophores located in the skin of this lizard. These effects are in turn largely under humoral control in this species (85); epinephrine (and excitement causing epinephrine release) result in splotchy melanophore contraction and consequent general lightening of skin (124), while a pituitary melanophore-expanding hormone produces darkening of the skin. Direct neural control of skin color response to high pressures is minimal, and isolated skin sections fail to show any color response to high pressure. Thus, the association of skin color changes with development of HPNS in the *Anole* suggests the possibility that changes in pituitary function may be associated with the other CNS effects.

V. EXPERIMENTAL MODIFICATION OF HPNS IN ANIMALS

It has already been mentioned that development of HPNS is not invariable for a given species or individual. It can be modified by pharmacologic means or by varying the conditions of compression. Since these variations are of considerable interest both from a practical point of view and because of their bearing on the etiology of HPNS, they will be reviewed briefly in the following paragraphs.

A. Temperature

Among the conditions of the compression environment, chamber temperature and noise levels appear to have only secondary effects on HPNS. In mice, chamber temperatures between 29 and 35 °C fail to affect convulsion thresholds, although at the highest temperatures tremor thresholds may be decreased slightly (about 3-5 ATA; (140)). In nearly poikilothermic baby mice and in poikilothermic lizards, temperature variations between 25-35 °C and 20-35 °C, respectively, fail to modify the characteristic development of HPNS. In liquid-breathing mice Lundgren and Ornhagen (101) report mean convulsion thresholds of 75 ± 9, 80 ± 12, and 90 ± 8 ATA for rectal temperatures of 27, 21, and 17 °C. At still lower temperatures, the mice fail to show HPNS convulsions, in much the same way as they have been shown to be unresponsive to other convulsant agents (43).

B. Noise

The only data available at present on the effect of noise refer to the relation between audiogenic seizures and susceptibility to HPNS. Audiogenic seizure-prone strains of mice are no more susceptible than resistant strains, and indeed no correlation could be detected between these two qualities (32). When mice of a normally audiogenic seizure-resistant strain are sensitized to such convulsions by exposure to high decibel noise at a critical age (75), their HPNS thresholds are no different from those of non-sensitized litter mate controls. However, during the late phases of stage II, squirrel monkeys appear to become susceptible to seizures evoked by photostimulation at the proper frequency (28) and the possibility that potentials evoked via other sensory modalities can produce similar effects during the pre-convulsive phase cannot yet be excluded.

C. Compression Rate

All observers agree that variations in compression rate do modify the development of HPNS in mammals (28, 47, 111, 130). In mice, squirrel monkeys, and rhesus monkeys the general relationship between convulsion threshold and compression rate is: $Pc = P_c^0 \ \underline{a} \log \dot{P}$, where Pc is the observed convulsion threshold, P_c^0 and $\underline{a}$ are constants, and P is the compression rate (33). In mice, this equation is based on a range of compression rates from 1 to 1000 ATA/hr, and the constants are: $\underline{a} = 16.8$ ATA, and $P_c^0 = 119$ ATA, if $\log {}^{10}P$ is used and $\dot{P}$ is expressed as ATA/hr.

Unlike the convulsion thresholds, the tremor thresholds appear to vary only slightly with compression rate. Data for the squirrel monkey suggest that the onset of stage II occurs between the fine tremor and the convulsion stages, depending on compression rate. Clinically, there is some suggestion that the syndrome that develops at high compression rates may be more severe than that seen at low compression rates. During rapid compressions, the tremor stage is shorter in duration, and the transition from stage I to stage II comes so early that stage I is often poorly marked. On the other hand, the underlying syndrome does not appear to change in kind. This is suggested by the continuous nature of the changes observed as compression rates are gradually increased, and also by the observation that the effect of inert gas narcosis on convulsion thresholds in mice is quantitatively the same at a moderate compression rate (40 ATA/hr) and a fast compression rate (600 ATA/hr) (32); (Fig. 12-14).

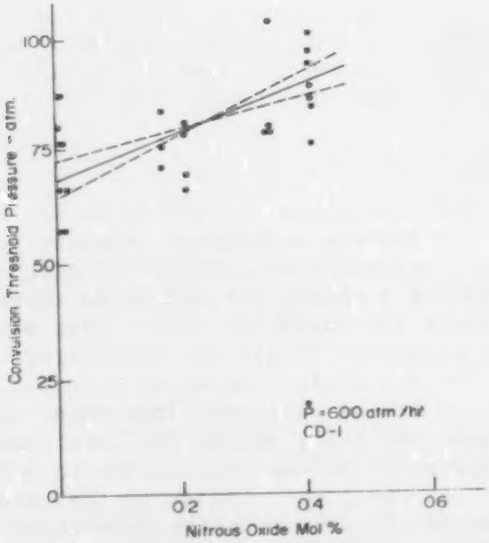


Fig. 12-14. Elevation of HPNS convulsion thresholds of CD-1 mice by partial substitution of helium by nitrous oxide in the compression atmosphere. Compression rate, 600 ATA/hr.

Staged compression experiments indicate that average rather than instantaneous compression rates determine HPNS convulsion thresholds in the mouse (32). Preliminary data for the baboon suggest that staging may provide even greater benefit than would be calculated from the average compression rate (Rostain, in press).

Finally, it is of interest to the etiology of HPNS that compression rate effects appear to be limited to the development of HPNS in mature mammals. By contrast, such effects are not demonstrable in birds, reptiles, amphibians, hamsters, or in young baby mice (33) and they seem likewise to be absent in invertebrates. This finding is of great theoretical importance because it indicates that compression-rate dependence is not an essential and invariable aspect of the effect of high pressures upon the central nervous system of vertebrates. Instead, one must now view HPNS as a composite entity involving the interaction of a purely pressure-dependent primary component and of a compression-rate-dependent secondary component modifying convulsion threshold pressures. Further work (29) indicates that the primary component is dominant at fast compression rates, that the secondary component modifies this by postponing seizures, and raising convulsion thresholds, and that monoamine neurotransmitters are important in the expression of this secondary effect (29).

D. Pharmacological Studies and Reserpine

Two agents which potentiate HPNS development are flurothyl and reserpine. Flurothyl, hexafluorodiethyl ether (Indoklon) is a convulsant fluoroanalogue of the general anesthetic diethyl ether. Added to the atmosphere in amounts below those capable of producing convulsions at 1 ATA pressure, this agent is capable of lowering HPNS convulsion thresholds in mice by as much as 60%.

The alkaloid reserpine is an agent of highly complex pharmacological action. Its most lasting effects, however, are linked to the depletion of monoamine transmitters, especially serotonin, from central nervous system synaptosomes. Mice, rats, and squirrel monkeys pretreated with effective doses of reserpine show a profound lowering of HPNS convulsion thresholds (Fig. 12-15) (29).

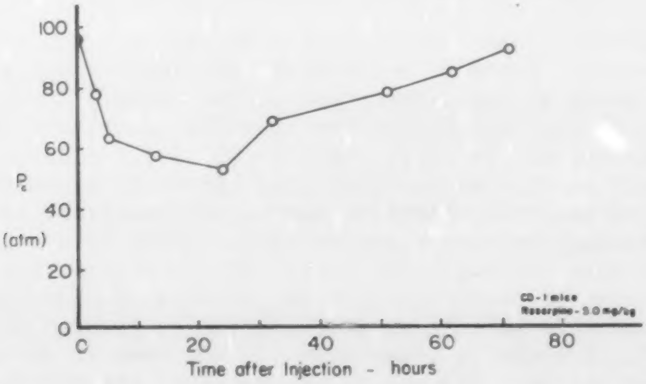


Fig. 12-15. Effect of time course of a single injection of 5 mg/kg reserpine upon HPNS convulsion thresholds in CD-1 mice.

In mice the relation of this effect to time elapsed between reserpine administration and compression has been studied. Lowering of convulsion thresholds begins soon after reserpine administration, increases during the first 12 hr, and then remains at a steady maximum level for about a further 24 hr, before gradually falling until the effect disappears about 72 hr after the original dose. This time course parallels the concentration of available neurotransmitters in the brain and suggests that lowering of HPNS convulsion thresholds is causally linked to the disappearance of one or several among serotonin, norepinephrine, and dihydroxyphenylalanine. Tryptophan can reverse about 20% of this effect of reserpine. Since tryptophan, administered after reserpine, speeds the restoration of normal brain serotonin levels, this finding further supports the hypothesis that this neurotransmitter plays an active role in the inhibition of HPNS convulsions.

E. Neuroanatomic Considerations

The site of action of high pressures upon the vertebrate organism is only very loosely defined at this time. Work concerning the myotatic reflex in the baboon as well as experiments with spinal transection (88) Brauer et al. (unpublished observations) establish that the site of action is not peripheral to the central nervous system, and that within the central nervous system the susceptible sites are superior to the spinal cord. Observations of HPNS convulsions in newborn mice and rats (105b) as well as in lower vertebrates (33) prove that the presence of a functional cortex is not essential. Finally, observations with implanted deep electrodes (79) suggest early involvement of elements of the ascending reticular formation, perhaps as far down as the lower brain stem. The complexities of the pharmacology of HPNS which are just beginning to emerge indicate that much further work is needed in this area before a satisfactory model can be proposed.

VI. PREVENTION OR AMELIORATION OF HPNS

Substituting other metabolically inert gases for helium in the chamber atmosphere produces interesting and important effects on HPNS. Very early in the development of the subject it was noted that substitution of hydrogen for helium seemed to increase the threshold for HPNS seizures in the rhesus monkey (27, 30). Subsequently, more extensive work in mice showed that this effect is closely related to the calculated narcotic effectiveness of the resultant atmospheres (32). Increasing the proportion of narcotically active gas in the mixture gave rise to progressively higher convulsion thresholds, and substitution of narcotically more potent gases for hydrogen produced comparable effects at lower partial pressures of the added gas. Indeed, it could be shown that the increase in mean convulsion threshold was uniquely related to the narcotic effectiveness of the chamber atmosphere and independent of gas density (Fig. 12-16).

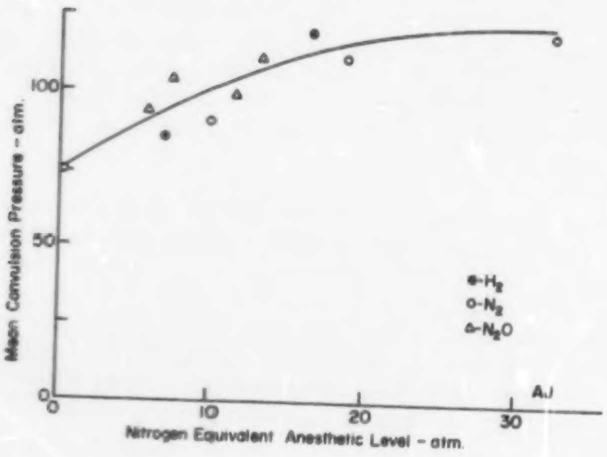


Fig. 12-16. Relation between calculated nitrogen equivalent anesthetic effectiveness of chamber gas at the time of convulsion to mean HPNS convulsion thresholds for helium-hydrogen, helium-nitrogen and helium-nitrous oxide mixtures. (Data from Figs 4-7 in Brauer et al. 1974a; Brauer & Way 1970.)

Based on studies of lipid solubilities of oxygen and other inert gas anesthetics, Paton (121) has suggested that O_2 is about 2.8 times more effective a narcotic than nitrogen. Other evidence indicates also that a nitrogen partial pressure of 10 ATA (isonarcotic with PO_2 of 3.6 ATA) does indeed raise mice HPNS thresholds perceptibly.

Expressing the results in terms of equinarcotic nitrogen partial pressures, it was found for instance that 10 ATA N_2 would raise the convulsion thresholds by about 25 ATA. This description probably underestimates the effectiveness of inert gas narcosis against the symptoms of HPNS.

Many years ago it was noted that the inhibition by chloroform of bacterial luminescense could be overcome by the application of hydrostatic pressure (56). Additionally, the narcotizing effects of ethanol on isolated nerves were shown to be reversed by pressure (144). A similar effect has been more recently demonstrated in newts. Narcosis produced in these animals by several gaseous and intravenous anesthetics can be rapidly reversed by application of hydrostatic pressures of 100 to 200 ATA (96, 97). These findings have been reproduced in mice. Such information has led Miller and his associates to formulate the critical volume hypothesis regarding the mechanism of action of anesthetic agents (111). They relate the anesthetic potency of an agent to the ability of its molecules to modify the dimensions of lipid phases, possibly those in cell membranes. It is theorized that anesthesia occurs when the volume of some hydrophobic region is caused to expand beyond some critical volume by adsorption of molecules of the anesthetic agent. This hypothesis accounts for the pressure reversal of anesthesia. It is argued that hydrostatic pressure opposes the lipid-layer swelling caused by anesthetic agents, resulting in the reversal of the anesthetized state. It should be noted that this hypothesis seems to correlate more closely with observed facts than do previous explanations of anesthetic action.

If pressure can reverse the action of anesthetics, it seems possible that anesthetics might reverse some of the effects of pressure. This might be the opposite effect of the pressure reversal of anesthesia. If symptoms and signs of HPNS are caused by a compression of lipid layers by hydrostatic pressure, then adsorption of molecules of the anesthetic agent into such lipid layers might reexpand them to their original dimensions. Measurements of changes in model membranes agree with this theory (19) (Fig. 12-17).

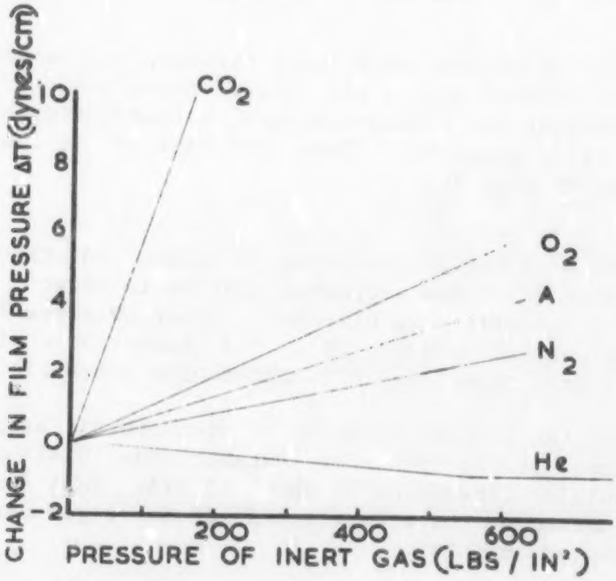


Fig. 12-17. Penetration of a lipid monolayer of egg phospholipid by inert gases, oxygen, and carbon dioxide at increased pressures. An increase in film pressure represents a comparable fall in surface tension. All the gases except helium adsorb to the model membrane. (Bennett et al. 1967). An increase in film pressure is equivalent to an increase in membrane volume.

In contrast to convulsions, tremor thresholds appear to be only about half as susceptible to the protective action of inert gas anesthetics (Fig. 12-18).

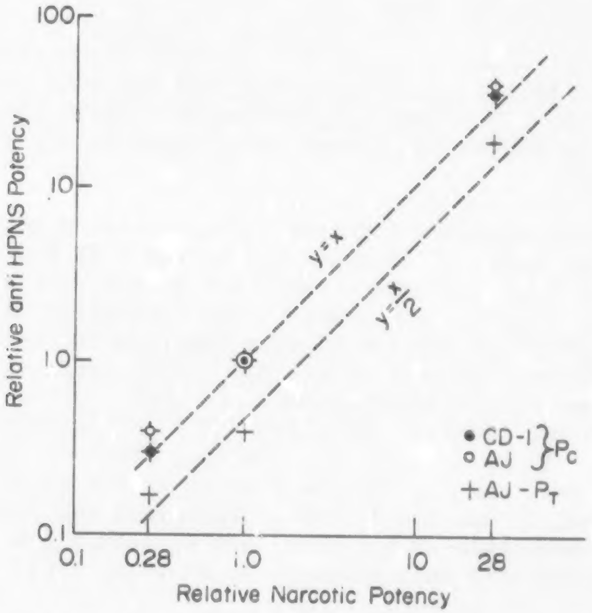


Fig. 12-18. Relation between relative anti-HPNS convulsant and tremor potencies and relative narcotic potencies of hydrogen, nitrogen, and nitrous oxide in CD-1 and A/J mice. (Data from Figs. 1-3 and 4-7 of Brauer et al. 1974; Brauer & Way 1970.) Log-log plot, with lines for y = x and y = x/2 indicated.

While it is not yet known to what extent other manifestations of the pre-seizure phases of HPNS are modified, one gains the clinical impression that squirrel monkeys at pressures in the HPNS range are far less distressed when breathing hydrogen-oxygen atmospheres than heliox. An isolated finding reported by Michaud et al. (110) has been that pressures of 36 ATA of H_2/O_2 are lethal to rabbits within 5-10 hours. The suggestion of these workers that this reflects biochemical activation of hydrogen and modification of key metabolic reactions seems to be refuted by the fact that mice and monkeys safely survive far higher partial pressures of H_2 for periods as long as, or longer than, those allegedly lethal to Michaud's rabbits (28, 130).

In line with what might be expected on the basis of experiments on reversal of narcosis (96), barbiturates, especially sodium phenobarbital, partially protect against HPNS convulsions (28). Animals thus protected can be carried to much higher pressures without lapsing into the severe convulsive syndrome. Work with squirrel monkeys suggests that the effect of barbiturates, like that of the inert gases, is considerably more pronounced on the convulsions than on the tremors of stage I (29).

In addition to the barbiturates, powerful anti-HPNS action has been found, especially in certain of the so-called central muscle relaxants with pronounced action upon transmission through polysynaptic reflex arcs, such as zoxazolamine, 2-amino-5 chlorobenzoxazole.

Diazepam (Valium), an agent of somewhat related pharmacological action, is less effective but is still capable of raising HPNS convulsion thresholds by 25 to 30%. More specific antiepileptic agents, including diphenyl-hydantoin sodium and trimethadione have so far given discouraging results.

Vigreux (148) examined nitrogen-helium-oxygen mixtures in man, using almost equal parts of nitrogen and helium (18% O_2, 42% N_2, 40% He). This mixture produced a reduction in the cost of the dive, increased thermal comfort, and lessened the distortion of speech due to helium. At depths to 262 fsw Vigreux reported the results were good, but at 394 fsw a mixture of 13% O_2, 43% N_2, and 44% He caused breathlessness and narcosis during moderate work. In an effort to reduce this problem, density equivalents (ED) in relation to air were calculated. Thus, the 262-fsw mixed-gas dive corresponds to an air dive of 174 fsw, and the 394-fsw dive to an air dive of 246 fsw. Using this method, it was found that a 50% oxygen and 50% nitrogen mixture had an acceptable ED for dives not exceeding 1 hr and, therefore, four mixtures were prepared as shown in Table 12-5.

Table 12-5. Oxygen-Nitrogen-Helium Mixtures for Deep Diving*

Depth msw	Mixture $O_2 : N_2 : He$	ED† msw
60	23 : 23 : 52	31
80	18 : 18 : 64	35
100	14 : 14 : 72	38
120	12 : 12 : 76	42

*Data evolved by Vigreux (1970)
†Density equivalent in relation to air

These mixtures proved effective, with no narcosis and satisfactory pulmonary ventilation during moderate work. However, Vigreux does not support his statements by scientific measurements.

As early as 1961 Zaltsman (154) reported that helium is antagonistic to the narcotic action of nitrogen, and investigated the use of nitrogen-helium-oxygen mixtures. For simplicity, Zaltsman used air-helium mixtures of 50% helium at depths from 197-328 fsw. This gave a maximum nitrogen partial pressure of 4.5 ATA, and oxygen did not exceed 2 ATA. Using such mixtures at 527 fsw, heavy work between 221-580 kg/m/min was possible with little or no tremor or signs of HPNS and apparently no thermal-balance or voice-distortion problems (Table 12-6).

Table 12-6. Characteristics of Air-Helium Mixtures Composed for Humans in Conditions of High Pressures*

Total pressure mH_2O	Mixture ratio %		Partial pressure of gases ATA		
	air	oxygen	oxygen	nitrogen	helium
From 60 to 100	50	10.4	0.7-1.1	2.8-4.4	3.5-5.5
from to 160	33	6.9	0.76-1.13	2.94-4.53	7.4-11.3

Decrease in thermal conductivity of each medium compared to helium-oxygen = 2.0 (60-100 mH_2O) and 1.65-1.9 (100-160 mH_2O); increase in density of medium compared to helium-oxygen = 2.1 (60-100 mH_2O) and 1.75-2.0 (100-160 mH_2O).

*Data from Zaltsman (1961).

However, there is again little quantitative data in support of these observations.

It is also possible that the high hydrostatic pressure at 1000 fsw or 30 ATA when using such a "trimix" nullifies any narcotic effect of the nitrogen present in the mixture.

Quantitative evidence of such a pressure antagonism was found by Proctor et al. (123) unintentionally. During decompression from 1000 fsw, the divers breathed a gas mixture (3.5 atm N_2, 1.0-1.5 atm O_2, and the balance helium) for 10 min at 600, 400, 240, and 200 fsw (19, 13, 11, and 7 ATA). At 600 fsw there were no narcotic effects or performance deterioration, but at the shallower depths the high nitrogen mixture caused narcosis. Presumably at 600 fsw the narcotic effect of the nitrogen was effectively balanced by the hydrostatic pressure. However, at the shallower depths the hydrostatic pressure was insufficient and nitrogen narcosis occurred.

Recently the value of trimix in deep diving has been confirmed at Duke University during dives to 720 fsw. Compression to 720 fsw in 20 min produced signs and symptoms of marked HPNS, including the appearance of marked tremor, nausea, dizziness, and performance decrement when using oxygen-helium alone. However, when 25% nitrogen was added to the oxygen-helium, compression in 20 min did not cause tremor or other HPNS signs or symptoms (Fig. 12-19).

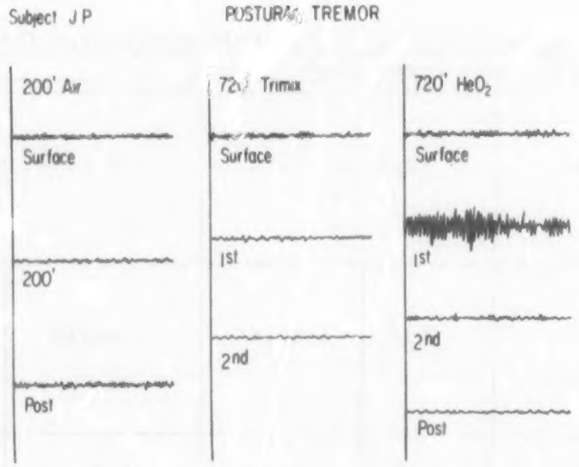


Fig. 12-19. Postural tremor measurements from a Grass SPA transducer on the index finger in a subject exposed to either air at 200 fsw, 25% N_2: 75% He: 0.5 ATA O_2 (trimix) or helium-oxygen (0.5 ATA). The compression rate was 60 ft/min with 1-minute stops at 50 fsw, 240 fsw, and 600 fsw. The nitrogen suppresses the resting tremor during the air dive and prevents the increase in tremor seen during the helium-oxygen dive by virtue of its presence in the trimix (25%) (Bennett, Blenkarn, Roby and Youngblood, 1974).

Indeed, even rest tremors at atmospheric pressure prior to the dive were less at 720 fsw (17d). However, signs and symptoms of nitrogen narcosis were noted.

More recently, the same prevention of HPNS signs and symptoms, such as tremors, nausea, and dizziness, has been achieved by utilizing only 10% nitrogen (17e). In these experiments five subjects were compressed to 1000 fsw (31 ATA) for 2 hr breathing 3.2 ATA nitrogen, 0.5 ATA oxygen, and the remainder helium. Compression took 33 min with a 10-s stage at 50 fsw (2.5 ATA), 1 min at 320 fsw (10.7 ATA), and 2 min at 700 fsw (22 ATA). Hypothetically, this 1:10 ratio for nitrogen-helium partial pressures should induce neither nitrogen narcosis nor HPNS. Tests of postural tremor, spontaneous electroencephalogram, psychomotor and intellectual activities, and subjective sensations were therefore made during the experiment. One diver worked underwater for 40 min on a simulated engineering assembly while breathing with a closed-circuit breathing apparatus and wearing a battery-heated suit in water at 56 °F. Decompression was accomplished in 4 days using 0.8 ATA oxygen and helium. Performance tests indicated no narcosis and little or no signs of HPNS. No tremor or EEG changes were seen. The "wet" diver reported sensations of mild euphoria, but the other four reported no difficulties. No HPNS nausea or dizziness was reported. Researchers concluded that using a ratio of 1:10: N_2: He is effective in the control of narcosis and HPNS during rapid compression to 1000 fsw (31 ATA).

Hamilton and his group have subsequently made similar studies at Tarrytown Labs and obtained the same result (71). The French COMEX group has also utilized nitrogen with helium-oxygen in dives to about 1200 fsw, using 9-10% nitrogen-oxygen-helium (inspired PO_2 approximately 0.4 atm). The compression schedule for this experiment (Coraz I) is illustrated in Fig. 12-20, and no tremors were observed after compression to 300 m in 4 hr.

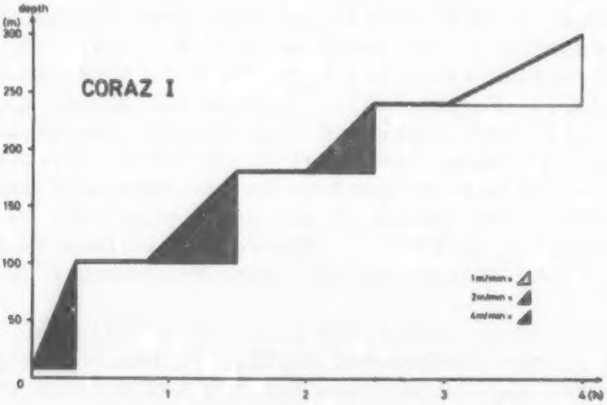


Fig. 12-20. Compression profile for Coraz I.

However, there was a serious problem of euphoria over a period of 2-3 hr, which meant that the men were unable to work or perform any task in the water. In all three subjects the EEG theta rhythm showed important changes, but one of the subjects displayed a completely random and unexpected paroxysmal discharge, which first appeared at a depth of 240 m and became more pronounced at 300 m (Fig. 12-21).

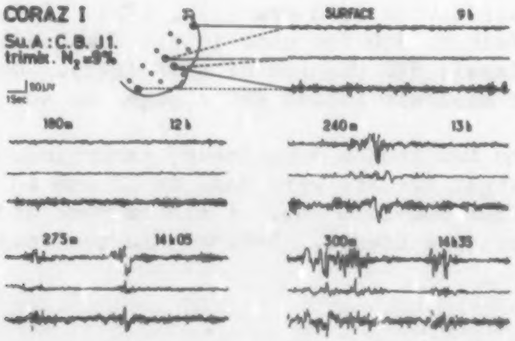


Fig. 12-21. EEG changes in Coraz I during the compression phase (explanation in the text).

This particular subject had previously been to 600 m without any abnormality in his EEG response. Twenty-four hours after the arrival at depth, EEG paroxysmal activities had disappeared, and theta waves were less important in the three subjects. It is not presently known if these effects were due primarily to the speed of compression or the gas mixture, but the preliminary results suggest that there are a number of problems, including variation in individual susceptibility, which are still not understood.

Other methods of postponing the development of HPNS are already in widespread use. There is no question that rapid compression rates not only generate the HPNS complex at shallower depths, but also augment the intensity of the symptoms (47, 97, 118). Conversely, slowing of compression rates has been shown to have opposite effects (26, 47, 120, 145). Additionally, Rostain and Naquet and Bennett and Towse (17a, b, 132) have suggested that staged compression offers definite advantages over continuous compression. In their experience, rest stops during which the CNS may accommodate to pressure have led to decreased symptoms. To date, the choice of any particular rate of compression has been empirical or arbitrary. The method devised by Fructus et al. (60, 61) based on Kylstra's concepts appears, however, to show promise.

Another method of ameliorating or preventing HPNS is to use excursion diving from a saturated depth. It has been observed that decompression from excursion dives permits quite large excursions without the need for stops (24). Excursion dives appear to provide one way to dive deep with fast compressions without undue HPNS (1a). The technique involves compression to a saturation depth, as described previously, followed some hours later by a fast compression to a work depth 150 fsw or so deeper, at rates which would not be possible from the surface. With such techniques it may be possible, for example, to make no-decompression excursions to 1400 fsw from 1000 fsw. However, whether or not HPNS would result with standard rates of compression of 60 ft/min has not yet been determined.

It is known that rates of 100 ft/min to 300 fsw do not elicit HPNS (17c) and that rates of 50 ft/min to 600 fsw will cause the syndrome (2) as will 16.7 ft/min to 600 fsw, from 600-1000 fsw, and also from the surface to 1000 fsw (17a, 17b). Indeed, even rates as slow as 3.4 ft/min to 800 fsw used in the New London experiment elicited the classic EEG changes of HPNS (123). Despite such a slow speed, computer analysis showed EEG changes at 400 fsw and deeper.

During the New London experiment, excursions which resulted in weakness and slight tremors were made at 27 and 28 ft/min from 800-1112 fsw, and from 800-1050 fsw. A slower rate of 17 ft/min a day later did not produce tremor. Neither did the very similar rate of

6.7 ft/min used by Buehlmann et al. (38) in excursions from 1000-1150 fsw. However, tremor, as shown by a decrement in the ball bearing test, was seen on compression from the surface to 1000 fsw. Results of the RNPL dive (17a, 17b) suggest that in some individuals, at least, a rate of 16.7 ft/min from 1000-1100 fsw and 1300-1400 fsw will cause EEG changes and tremor.

A recent experiment at Duke University known as Deep Work 1000 (1a) involved the compression of six men to 850 fsw over 2 days, with four stages and three rates of compression, 25 ft/min (0-450 fsw), 10 ft/min (450-600 fsw), and 2 ft/min (600-870 fsw). During the 4 days at 870 fsw three of the subjects together made excursions to 1000 fsw on different days at 16.7 ft/min, 50 ft/min, and 100 ft/min. During the first 20 min of the 2 hr at depth, measurements were made of postural and intentional tremor, EEG, performance on the ball bearing test, the Wechsler-Bellevue Digit Symbol Test, the Purdue Peg Board, and arithmetic. One of the subjects then carried out various tasks and postural-tremor tests underwater. A further test battery was given at the end of the 2 hr. There was no significant increase in tremor over the 2 hr; similarly, no significant psychomotor decrement (Table 12-7) occurred, regardless of the rate of compression.

Table 12-7. Performance Efficiency During Excursion from Saturation at 870 fsw to 1000 fsw at 100 ft/min.

Test		Predive test 4	870 fsw (Pre-excursion)	Arrival at 1000 fsw 100 ft/min	1 3/4 hrs at 1000 fsw 100 ft/min
Ball-bearing	Mean	15.67	19.00	18.33	18.33
	SD	±3.79	±2.08	±2.08	±2.08
Pegboard	Mean	28.67	32.67	31.33	30.00
	SD	±3.26	±4.73	±4.51	±1.00
Visual analogy	Mean	47.00	49.33	51.00	48.33
	SD	±6.25	±5.51	±7.00	±2.31
Arithmetic Correct	Mean	11.00	8.00	9.00	13.33
	SD	±5.57	±8.89	±7.81	±8.08

The EEG showed no evidence of a compression-induced rise in theta activity (4-6 Hz) but there was a reduction in the overall EEG energy, which was more evident in the alpha and beta than in the delta and theta frequencies.

We interpret these results to mean that such excursions do not elicit the signs of HPNS induced by over-rapid compression, but that the depression of the EEG due to hydrostatic pressure is present. Further, we concluded that a standard excursion compression rate of 60 ft/min from 870 fsw would be unlikely to precipitate serious HPNS. Additional study is needed before this data may be extrapolated to depths beyond 1,000 fsw, because it seems that the deeper the saturation depth, the slower the rate of compression to excursion depth must be, and the greater the excursion depth from the saturation depth, the slower the rate of compression must be.

For example, in the 1500-fsw RNPL dive, one subject experienced confusion and a sense of impending loss of consciousness at 1535 fsw during a recompression from 1170 fsw designed to relieve vestibular decompression sickness in another subject (17a, 17b). The pressure was increased in a series of short compressions and stages over 8 1/2 hr. However, only 10 hr were spent at 1500 fsw, and the 20-hr cycle of EEG change continued during the decompression, which may have been partially responsible for the effects. Nevertheless, even though the subject had spent 3 days deeper than 1000 fsw, he was unable to tolerate a 365-fsw excursion from 1170 fsw despite such a slow rate of compression.

Clearly, much more research is required in this critical area, with careful measurement of HPNS to identify the operationally optimal rates of compression both for deep-saturation and excursion dives.

VII. ETIOLOGY OF THE HIGH PRESSURE NERVOUS SYNDROME

Many diverse factors have, at one time or another, been suggested as contributing to the genesis of HPNS. These factors may be conveniently divided into two categories: indirect and direct effects of increased ambient pressure. Indirect effects of depth include alterations in the partial pressure of oxygen and/or carbon dioxide, as well as alterations in temperature. More direct effects of exposure to depth would include osmotic gradients produced by dissolving of gases, possible toxicity of the diluent gas under pressure, changes induced by the increased mass of gas dissolved in tissues, and direct effects of hydrostatic pressure itself. This section will present the evidence both for and against the possible etiologic role of each of these factors and attempt to assess the likelihood that a given factor is responsible for the HPNS complex.

A. Oxygen

Previous mention has been made of the fact that some symptoms of HPNS are also found in some pathological processes. Lucien and Barthelemy (100) noted certain similarities with the symptoms of altitude hypoxia. They postulated that CNS hypoxia was present because of impaired oxygen diffusion secondary to increased gas density at depth. Chouteau et al. (40a) noted that some HPNS symptoms in experimental animals could be reversed by increasing the inspired partial pressure of oxygen. Histoenzyme analyses in animals exposed to a 29 ATA helium-oxygen atmosphere containing 1.6% oxygen (0.46 ATA) for up to 4 hr revealed changes suggestive of histotoxic anoxia (109). In this experiment, however, the animals died during the pressure exposure, so that the observed changes could have taken place during the immediate post-mortem period. Conversely, Overfield et al. (119) found that in human subjects exposed to 31.3 ATA (1000 fsw) on a helium-oxygen mixture containing 0.9% oxygen (0.28 ATA) respiratory gas exchange remained normal. Arterial PO_2 values were consistently within normal limits, even though this gas mixture had four times the density of air at sea level. Additionally, using various mammalian species, other investigators found convulsion threshold pressures to be independent of PO_2 in the oxygen ranges of 0.4-2.0 ATA (30, 32a).

The similarity between the generalized seizures seen in HPNS and those occurring because of CNS oxygen toxicity would suggest that excess oxygen might be implicated. The study by Overfield et al. (119) previously cited demonstrated a lack of such excesses. The studies by Brauer and his coworkers (30) did show that with a PO_2 of 2.4 ATA or greater, convulsion threshold pressures were decreased, but this level of oxygen is much higher than those generally utilized. They also discovered significant differences between susceptibility to HPNS convulsions and susceptibility to oxygen convulsions in various species (28). Additionally, gamma aminobutyric acid (GABA) has been shown to decrease in cases of CNS oxygen toxicity (149). However, in mice exposed to a normoxic helium atmosphere for 24 hours at 20, 40, or 60 ATA, analysis of brain tissue after decompression revealed a linear increase of GABA with pressure (128). The exact role of GABA in oxygen toxicity is not completely clear, but such opposite findings, combined with the other studies cited, would imply that in normoxic helium atmospheres, oxygen probably plays no more than a minor role in the etiology of HPNS.

In other studies already discussed in conjunction with the EEG concomitants of HPNS, oxygen partial pressures below 2 ATA were found to have a negligible effect upon the convulsion thresholds of mice, while pressures of 2 ATA or above lowered HPNS thresholds in mice (30), and may have raised them in rats ((17), but see (1), (47)). In squirrel monkeys, HPNS developed equally at a PO_2 of 0.5 and of 1.5 ATA (28). Implications of these negative findings are borne out in squirrel and in rhesus monkeys (Fig. 12-22) by studies of blood gas composition which fail to reveal any consistent changes in either oxygen or CO_2 content even in late stage II preparations on the point of convulsions.

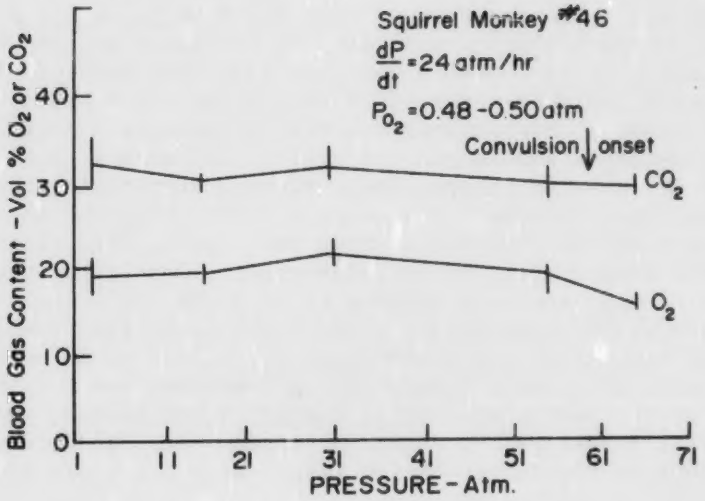


Fig. 12-22. Total blood oxygen and CO_2 content in a squirrel monkey during a simulated dive to the point of HPNS convulsions. (He-0.5 atm O_2, 32° C).

The absence of consistent changes in respiratory rate in rats (1) and squirrel monkeys (28) likewise fails to indicate any degree of respiratory impairment up to the convulsions of stage III. Finally, comparison of equinarcotic He/H_2, He/N_2O, and He/N_2 mixtures shows that the same mean convulsion threshold pressures occur in mice in equinarcotic gas mixtures of widely different density (Fig. 12-23).

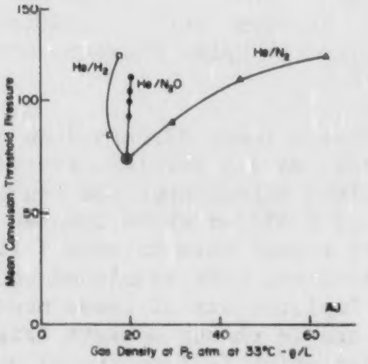


Fig. 12-23. Relation between density of chamber atmosphere at the time of convulsion to mean HPNS convulsion thresholds for A/J mice in helium-hydrogen, helium-nitrogen or helium-nitrous oxide at atmospheres. (Data from Figs. 4-7 in Brauer et al. 1974a; Brauer & Way 1970).

These results of animal experiments agree well with the results of human experiments which have revealed that respiratory exchange is adequate for moderate exertion even at atmospheric densities corresponding to 180 ATA (147, 150).

B. Gas-Induced Osmosis

Indirect effects of increasing ambient pressure can perhaps affect the appearance of HPNS. However, even though increased temperatures may accelerate its development, none of these factors seem to be primarily responsible. One of the more direct effects, gas-induced osmosis, has been suggested as a cause. Osmosis generated by dissolving inert gases was first demonstrated by Kylstra et al. (87). Such osmotic pressures may lead to fluid shifts between the various body compartments. Hills (76) has implicated this phenomenon in the development of arthralgia and vestibular disturbances during compression as well as in the development of aseptic osteonecrosis in divers. Others have extended these concepts to include the manifestations of HPNS (Fructus et al. (in press)). It is reasoned that onset of symptoms during rapid compression results from fluid shifts generated by saturation gradients of inert gas between hydrophilic rapid tissues (such as blood) and hydrophobic slow tissues (such as the CNS). Similarly, equilibration of these gradients would account for the decrease in symptoms after some period at stable pressure. However, the osmotic pressures generated in Kylstra's experiment were very short-lived, no longer than 20 min. As has been previously noted, HPNS symptoms may require 12 to 18 hr to abate after reaching stable pressure. Even then, base-line levels may not be reached. Ornhagen and Lundgren (118) found that in liquid-breathing mice where there was no gas phase and hence no increase in gas partial pressures, rapid compression rates generated convulsions at lower pressures. Obviously, saturation gradients of the type described above could not be causing this lowering of convulsion threshold pressure. Additionally, the persistence of certain of the features of HPNS, despite bottom times of 100 hr or more, would suggest that although gas-induced osmosis may be playing some role, it is certainly not the only etiologic factor. Any saturation gradients that might be operative would almost surely reach equilibrium during such a prolonged period at depth.

C. Diluent Gas

Saturation gradients could be produced by any inert gas. However, the diluent gas could conceivably be producing some direct effect itself, by virtue of its own molecular properties. A number of studies have shown that helium and neon possess no narcotic properties of the nitrogen type (9, 15a, 19, 21, 23, 27a, 30, 71, 105a, 120, 129).

Helium and neon do not appear to penetrate phospholipid membranes, so that this lack of narcotic potency would be expected (19).

If HPNS were a manifestation of helium narcosis, one would expect changes in the symptom complex if the diluent gas were abruptly switched at depth. Hamilton (71) has shown that such changes do not occur. Cognitive performance, memory, and learning ability--factors markedly affected by increased partial pressures of nitrogen--show no decrement at increased partial pressure of helium (21, 23, 120).

Metabolic Implications. If inert gas narcosis cannot be implicated, could helium produce some metabolic or toxic effects leading to HPNS? Helium, possessing a thermal conductivity approximately six times that of air, increases basal metabolic rate in response to heat loss. The magnitude of this response is proportional to the thermal gradient between the organism and the environment (95). However, if ambient temperature is kept stable and near body temperature, this response can be eliminated. Even more basic metabolic alterations have been observed. South and Cook (142) demonstrated that substitution of a normoxic helium atmosphere for air at 1 ATA resulted in changes in both aerobic and anaerobic glycolysis of mouse liver slices. Featherstone et al. (53) suggest that inert gas molecules may be altering protein function by binding at critical sites. Other investigators have observed that the growth rate of certain bacteria and fungi is altered by changing the diluent gas in the atmosphere (46, 55, 139).

Apparent toxic effects have been observed in skeletal muscle (74) and cardiac mitochondria (73) of mice maintained in a normoxic helium atmosphere at 1 ATA for 90 days. The author of these studies notes that these effects could have been the result of nitrogen washout, rather than of helium exposure. An identical atmosphere, also at 1 ATA, produced human EEG changes, such as increased theta and delta waves and decreased alpha waves and distinct helium tremors after an exposure of 4 hours (78). Although the other effects cited above cannot be readily correlated with HPNS, the distinct similarities found in this latter study must be considered, for it seems that the term inert gas may prove to be inaccurate when applied to gases of the helium group.

D. Direct Effects of Hydrostatic Pressure

There is ample evidence to establish the fact that at pressures of 50 to 150 ATA, the range in which the HPNS develops in vertebrates, there are a wide variety of changes in cell structure (159), membrane permeability (35), ciliary activity (57, 84) axon conduction (68), cell replication (103, 106), and other basic phenomena; even in relatively simple chemical systems changes in dissociation constants (45), in ion hydration (77) and in macromolecular configuration (7) can be detected at these or at only slightly higher pressures.

Two alternative theories of the etiology of the HPNS require comment. First is the suggestion that the HPNS is merely a manifestation of central hypoxia secondary to respiratory impairment due either to excessive respiratory work or to impaired alveolar oxygen diffusion in the dense high pressure atmospheres (40). Second is the suggestion that uneven distribution of dissolved gases between blood and tissues during rapid pressure changes results in temporary osmotic imbalance and fluid shifts which are responsible for the hyper-irritability and the compression rate dependent characteristics of the HPNS convulsions (130, 87).

As far as the basic events of the HPNS are concerned, both of these hypotheses are disproved by the fact that HPNS hyperexcitability and convulsions have been produced by hydraulic compression in the absence of any gaseous atmospheres, in fluocarbon-breathing mice (88, 101), in water-breathing newts (112), and fish (5). With respect to the second hypothesis, a further pertinent observation is that compression rate effects are absent in heliox-breathing birds weighing several times more than the mice, and about as much as the rats, in both of which compression rate effects are readily documented (33).

Yet the HPNS is a complex entity, and the possibility that each of the above hypotheses may contain a grain of truth and contribute to the pattern of development of the syndrome under particular conditions cannot be rejected out of hand but needs to be examined in greater detail. These findings would imply that some aspect of hydrostatic pressure itself is a major factor, rather than the concentration of dissolved gas molecules.

Such a suggestion is not at all unreasonable, for hydrostatic pressure is known to have ubiquitous effects in physical, chemical, and biological systems (157, 158). For example, classical gas laws do not hold true at extreme depths; dissolved gases may behave differently under such conditions (52) and liquids, usually thought of as being incompressible, display volume decreases with concomitant increase in viscosity (56). Under extreme pressures, gases may form solid hydrates and clathrates and cause increased ordering of water molecules (46, 53). Since ionization of a solution leads to a decrease in volume (charged particles attract water molecules, producing electrostriction; the greater the number of charged particles, the greater this effect and the less the volume), pressures tend to favor ionization (81, 122) and alter pH (56, 113). Molecular volumes can be altered by pressure (81, 113). This may cause marked structural changes in complex molecules, leading to such effects as protein denaturation (53, 146).

Biological proteins and enzymes are very large and complex molecules. Because of this, molar volume changes associated with enzyme activation and substrate reactions are sometimes quite large. As Landau (91) observes, in any enzyme-substrate reaction involving an increase in volume, hydrostatic pressure would be inhibitory. If such a reaction resulted in volume decrease, the result would be stimulation; if no volume change occurred, hydrostatic pressure would have no effect on the reaction. This relationship has held true for numerous bioenzyme systems. Aggregation of a variety of enzymes with their substrates results in an increase in molecular volume, and hydrostatic pressures inhibit such aggregation.

Among these enzymes are included sickle-cell hemoglobin (115), ribonuclease S_1 (113), fibrin (116), myosin (83), flagellin (64, 160), and beta-galactosidase (92). Adenosine triphosphatase also appears to be pressure-sensitive (67, 89). Glycolysis is inhibited, since this reaction involves a volume increase of 24 ml/mole (55, 56). Gel-sol transformations, which involve volume changes, are altered by pressure (55, 91, 107). Johnson and Eyring (81) reason that probably all biological processes have an optimum pressure, just as they have an optimum temperature. What influence changes in enzyme systems may have on the development of HPNS is unknown, but the possibility of some such relationship cannot be dismissed.

Hydrostatic pressure also affects more complex systems such as isolated biological tissues. Erythrocytes lose their biconcave shape and become spherocytic at high pressures (56). Isolated muscle preparations display enhancement of tension development (56, 97, 122), and at extremely high pressures they become rigid. The frog-skin preparation undergoes a pressure-related increase in membrane permeability to sodium ions with increased membrane potential (30). Nervous tissue also shows pressure-related changes. Isolated frog nerves display increased excitability, increased action potential amplitude, and increased conduction velocity under increased hydrostatic pressure. These changes are reversible upon lowering the pressure (69, 143). Similar pressure exposures utilizing the giant axon of the squid yield similar results with only minor differences (144). This hyperexcitability of isolated nervous tissue may have some bearing on the hyperexcitability phase of HPNS in animals described earlier.

In this regard intact organisms, like isolated tissues, are susceptible to hydrostatic pressure. Some bacteria show inhibition of growth under pressure (55, 56). In other, pressure increases resistance to high temperatures. Probably because of effects on gel-sol transformations, ameboid movement and pinocytosis in amebas are inhibited by pressure, and the organism will eventually become spherical (56, 107). Marine organisms are likewise affected by hydrostatic pressure. Shallow-water amphipods and crustaceans display increased locomotor activity up to pressures of 100 to 150 ATA. At greater than 200 to 270 ATA locomotor activity is completely inhibited. These changes are completely reversed within 2 min at 1 ATA (102). Some fish may display cardiorespiratory inhibition if taken to depths greatly beyond those to which they are accustomed (4). Amphibians, such as newts, lose their righting reflex between 100 and 200 ATA when compressed hydraulically (96). Application of hydrostatic pressure to liquid-breathing mice (no gas phase, hence no increase in gas partial pressures) leads to the development of tremors, incoordination and seizures indistinguishable from the HPNS complex seen in gas-breathing mice (88, 118).

It can readily be seen that hydrostatic pressure causes many alterations in biological systems. It is important to know the site where pressure acts to cause HPNS in divers. Good indications are given by the results of some further animal experiments. Pithed frogs develop twitching of their toes when subjected to high hydrostatic pressures (55). However, isolated hind limbs do not contract at all, even at 200 ATA (88). Additionally, if the spinal cord of a liquid-breathing mouse is sectioned and the animal is then pressurized, muscles distal to the section remain flaccid and develop none of the signs of HPNS. Those muscle groups supplied by cord tissue proximal to the section will develop such signs.

These findings indicate that HPNS is correctly termed a nervous syndrome, for it seems that the symptoms and signs are originating in the central nervous system. Chouteau et al. (40a) concluded from their experiments with baboons that the basic function of the neuromuscular system was unaffected in HPNS. Rather, they suggested that spinal and supraspinal neuromotor regulatory centers were altered. Bachrach and Bennett (2) have recently reviewed the pathways and centers involved in tremor. Prominent in these pathways are midbrain centers, the ascending reticular system, the basal ganglia, and portions of the thalamus. It is proposed that these areas are activated by increased ambient pressures (15a). This is in agreement with the findings of Zaltsman and Brauer, previously cited. Further, Brauer (26) has demonstrated that cerebellar ablation sensitizes an animal to HPNS convulsions. Helium-oxygen atmospheres under pressure seem to facilitate impulse spread in the CNS (27a). Increased conduction velocity in isolated nerves compressed hydraulically has been previously discussed. Brauer states that his data suggest that development of HPNS involves pathways originating largely in the brainstem and impinging on the midbrain and limbic system. These pathways probably involve monoamine transmitters. Current work seems to indicate that serotonin may play an important role. Obviously, too little is known at present to make definitive statements regarding the exact mechanism by which pressure affects the central nervous system. It seems that its effects are certainly profound, and that hydrostatic pressure is probably of primary importance in the development of HPNS. It may be necessary in the future to consider the effects of hydrostatic pressure as drug effects.

E. Carbon Dioxide

In addition to changes in oxygen levels, an increase in carbon dioxide level was suggested as a possible etiologic factor in the genesis of HPNS (13) when HPNS was first noted. Several authors have noted increased alveolar PCO_2 during deep dives, especially during exercise (80, 136, 138). This has been attributed to decreased alveolar ventilation secondary to gas density, but Schaefer et al. (138) noted that experienced divers tended to retain carbon dioxide during dives even while at rest. This was explained on the basis of a characteristic breathing pattern seen in trained divers that led to increases in alveolar PCO_2, mixed expired PCO_2, and urine CO_2 excretion. Arterial levels of carbon dioxide were not stated. Conversely, Overfield et al. (119) in the dives cited previously, found an absence of CO_2 retention in trained divers, with arterial partial pressures of carbon dioxide ranging from 30.5 to 42 mm Hg. Using mice pretreated by intraperitoneal injection of either saline or THAM buffer as a control, Brauer (26) and Brauer et al. (31) found that there was no significant difference in convulsion threshold pressures of the two groups. Additionally, it was noted that HPNS symptoms will develop even in CO_2-free atmospheres (25a). It should be noted that the characteristic response to increased carbon dioxide tensions in the absence of hypoxia bears little resemblance to the symptomatology of HPNS. This fact, when combined with the variable carbon dioxide levels that have been observed without corresponding variability in the HPNS manifestations and with the lack of effect of buffers, leads to the conclusion that carbon dioxide retention, like variations in oxygen levels, probably plays no causative role in HPNS.

VIII. RESEARCH NEEDS

A. Immediate Applied Research Needs

1. Diagnosis of HPNS Stages: Taxonomy and Clinical Clarification of Signs and Symptoms

Communication among the various international laboratories studying HPNS has generally been good. Exchange of information as well as equipment and personnel has been effectively accomplished. Such interaction has underscored a need for further refinement of the taxonomy of signs and symptoms and the diagnosis of stages of HPNS so that we may make certain that all investigators are collaborating in identifying the relevant variables in HPNS and are describing and measuring the same phenomena. Illustrative of the problem is the description of tremor, a major symptom of HPNS, without specifying type (e.g., intentional or postural) or means of measurement (i.e., observed by experimenter, reported by diver, or quantitatively measured). A similar problem exists with the non-specific use of terms such as "vestibular hit" to define an event or series of events (such as imbalance and nausea) which may actually be centrally mediated. To refer to this as "vestibular" may erroneously suggest an etiology.

2. Vigilance, Microsleep, Sleep Disturbance, and Fatigue

Fatigue, sleep, drowsiness, and the associated loss of vigilance are commonly part of HPNS in very deep diving. Experiments which will define the criteria of compression profiles and gas mixtures which induce these phenomena and the means for their prevention are required. The physiological basis of these 'sleep' phenomena needs research to determine the nature of the CNS changes responsible, so that their eventual significance can be assessed.

3. Vestibular System Involvement

Although no direct involvement of HPNS with malfunction of the vestibular system has been proved, as it has for the CNS, it is believed that HPNS may well involve disturbance of CNS pathways through which vestibular mechanisms are processed. Classification of these mechanisms, how they work, and which CNS pathways are involved is required. For example, it is suggested that some motor disturbances of HPNS may be the result of facilitation of central-vestibular pathways via the cerebellum. These and other possibilities need verification. Other comments on vestibular associations will be found in the report by the Vestibular Panel.

4. Visceral and Autonomic Effects

While EEG anomalies, changes in locomotor function, and loss of vigilance are among the most prominent signs of HPNS, the question of whether the seeming absence of autonomic effects conceals significant alterations in regulatory capabilities such as thermal regulation, cardiovascular function, and respiratory function needs to be investigated systematically because of its importance to the diver's ability to withstand environmental stress.

B. Practical Problems

1. Selection of Personnel

Owing to evidence of wide individual susceptibility to HPNS, the ability to select personnel for resistance to one or more phases of HPNS would be of significant practical value. There is evidence indicating that HPNS resistance is a stable individual characteristic, so that the objective of personnel selection seems realizable in principle, provided appropriate selection criteria can be determined.

2. Compression Profile

Only a limited number of deep dives have been achieved, but these have established the importance of determining the appropriate compression profile to minimize signs of HPNS. It is vital to the health, safety, and efficiency of the diver that the necessary profiles be determined as soon as possible to permit deep diving, both chamber and open-sea, to continue. Possible variations of dive profiles include: variations in the time course of continuous compression, the use of stages in descent, and the combining of various forms of saturation/excursion dives.

3. Accommodation and Adaptation

Accommodation describes the fact that certain signs of HPNS decrease in magnitude with time of sojourn. This effect is not uniform for all HPNS signs, a finding hardly surprising in view of the complexity of the etiology of HPNS. Careful evaluation of HPNS signs and symptoms with prolonged sojourns and with repeated exposures to great depths is needed to assess the extent to which adaptation and accommodation phenomena may be relied upon for amelioration of HPNS effects in deep-diving operations.

4. Temperature Effects

Effects of temperature on susceptibility to HPNS remain uncertain. Human anecdotal data suggest that increased temperatures increase susceptibility to HPNS. In view of the known complexity of the thermal environment in deep diving and the fact that temperature distribution in divers may be manipulated to a great extent, detailed information of temperature control is urgently needed. In a similar fashion, the effects of cooling--such as occur in open-sea operations--may be ascertained by systematic investigation of temperature control.

5. Environmental Setting: Open-sea Dives vs. Chamber Dives

Transferring diving experiments from the chamber environment to the open-ocean work dive could be expected to modify manifestations of HPNS. At present, the importance of this factor and even the direction of possible changes is unknown. Effective open-sea physiological monitoring is urgently needed to assess HPNS effects at depth. This is of particular importance as greater diving depths are attained because of the possibility that important warning signs heralding more severe HPNS manifestations may be obliterated or not detected in the open-sea environment. Such a possibility makes the discovery of additional indices of physiological disturbance even more urgent.

6. Prophylaxis and Treatment

The group of inert gases with measurable anesthetic potency is to date the one firmly established type of pharmacological agent which modifies HPNS effects in all species, including man. Even here, evidence which shows the effects are not simple is beginning to emerge. Dose-response relations and compression-rate effects on different components of the HPNS are not uniform, and systematic investigation is indicated if this powerful tool is to be applied effectively to operational diving. There are indications that other pharmacological agents such as injectible anesthetics, centrally acting muscle relaxants, and a variety of agents acting upon cholinergic and adrenergic junctions in the nervous system can modify HPNS effects. Pharmacological manipulation of HPNS serves two purposes: it may lead to control and amelioration of HPNS effects, and it will increase our understanding of HPNS etiology. Further work is therefore of great theoretical and practical importance.

C. Implications of HPNS for Deep Diving

1. Performance Decrement

The demonstrated combination of loss of vigilance and neuromuscular disturbances, such as tremor, result in a modification of diver performance in a complex but highly characteristic fashion. Further evaluation of the ability of the diver to perform skilled work reliably at various stages of HPNS is critical. Results available to date suggest little correlation between electrophysiological and neuromuscular measurements of HPNS and performance decrement, either because performance measures are relatively insensitive, or because HPNS may in fact not cause performance degradation. This urgently needs further investigation.

2. Residual Effects of HPNS Exposures

Although to date no conclusive evidence of irreversible changes as a result of HPNS, of whatever degree of severity, has been obtained, subjects studied have experienced limited numbers of deep exposures and, moreover, the relative recency of human deep diving has not provided an opportunity to obtain data on which to base a trustworthy set of conclusions. Accommodation and adaptation to hyperbaric conditions are known to exist; quantification of long-range HPNS effects would aid in determining the implications of accommodation and adaptation for human diving. With the spread of deep diving exposures, the early development of this vital body of information becomes of the utmost importance.

3. Choice of Optimal Procedures

With the availability of a variety of agents and procedures to modify the development of the different components of HPNS, it should be possible to tailor optimal compression procedures to many different sets of operational requirements by varying compression profiles, stages during compression, gas mixtures, premedications, and perhaps thermal regime. Systematic studies of these kinds are clearly indicated.

D. Basic Mechanisms Requiring Research

1. Anatomical Sites of HPNS

Present indications are that HPNS involves functional changes in CNS activity at a level above the spinal cord. To understand the etiology of HPNS fully, and to anticipate the variety of HPNS effects upon various body functions, further work is needed. Results of such studies are essential as the basis for HPNS prevention and therapy.

2. Neurophysiological Substrates

It will be necessary to determine whether the changes in neural function associated with HPNS can be reproduced at the cellular level or whether a more complex array of nerve cells is required for high pressure excitability to appear.

3. Biophysical and Biochemical Mechanisms

Developing optimal compression procedures and insight into biophysical and biochemical mechanisms is critical. A promising beginning in this direction has been made in studies of inert gas and high pressure effects, but it is becoming clear that other, as yet unknown mechanisms are important and play a role in the course of HPNS development.

4. Role of Neurotransmitters

Suggestions that the synapse between two nerve cell bodies is a site particularly vulnerable to modification under a high pressure environment implies that release of one or several neurotransmitter substances involved in neural impulse transmission in the brain could be involved in the origin and development of HPNS. Pharmacological studies to clarify this are needed.

5. Compression-Rate Dependence

Two major problems appear to be important in HPNS compression-rate dependence studies: 1) profound differences among the various manifestations of HPNS, which imply that the clinical picture of HPNS will vary widely with different compression rates and compression profiles; 2) the apparent existence of both compression-rate-dependent and compression-rate-independent components, which combine to produce HPNS in higher vertebrates. Since an understanding of these elements is essential to the development of optimal compression procedures and possible pharmacological control of HPNS under differing compression conditions, further analysis of this problem is important.

6. Comparative Physiology: Relationships and Significance of Signs and Symptoms in Man and Animal

Animal studies have great relevance for the study of human pathophysiology and behavior. Many experiments which explore functional components of HPNS can be accomplished in animals. In particular, identifying those symptoms of HPNS which occur in both human and animal subjects is required if the several procedures being tested are to be properly interpreted.

The following laboratories are currently working on various aspects of HPNS. It is from these institutions from all over the world that the research findings included in this report have been drawn. The number and geographical spread of these research facilities is an indication of the importance and urgency of HPNS research, and it is from these same laboratories that data leading to the eventual control of HPNS may come.

LIST OF MAJOR LABORATORIES CURRENTLY WORKING ON HPNS

United States

1. F. G. Hall Environmental Laboratory
   Duke University Medical Center
   Durham, North Carolina

   P. B. Bennett

2. Institute of Marine Biomedical Research
   University of North Carolina
   Wilmington, North Carolina

   R. W. Brauer

3. Institute of Environmental Medicine
   University of Pennsylvania
   Philadelphia, Pennsylvania

   C. J. Lambertsen

4. Naval Medical Research Institute
   Bethesda, Maryland

   A. J. Bachrach

OTHER LABORATORIES ENGAGED IN HPNS WORK

5. Anesthesia Department, Harvard Medical School
   Boston, Massachusetts

   K. W. Miller

6. Anesthesia Department, University of California
   San Francisco, California

   T. Eger

7. Department of Anesthesia, Stanford University
   Stanford, California

   J. J. Kendig

8. S.U.N.Y. at Buffalo, New York

H. Rahn

9. Tarrytown Labs, Ltd.
Tarrytown, New York

R. W. Hamilton

United Kingdom

10. Pharmacology Laboratory
Oxford University
Oxford, England

W. D. M. Paton

11. Physical Chemistry Laboratory
Oxford University
Oxford, England

E. B. Smith

12. RNPL (Royal Navy Physiological Lab)
Alverstoke, Nants, England

H. V. Hempleman

France

13. CNRS (Centre National de la Recherche Scientifique)
Institute de Neurophysiologie et de Psychophysiologie
Marseilles, France

J. C. Rostain

14. COMEX
Marseilles, France

X. Fructus

15. Lab de Physiologie Nerveuse
Gif-sur-Yvette, France

R. Naquet

16. Lab de Psychophysiologie
University de Provence
Marseilles, France

M. Hugon

17. GISMER B. Broussole
CERTSEM Toulon-Naval Base, France E. Guillerm
CERB J. LeChuiton

18. Universite de Aix
Marseilles II, France

J. P. Charpy

Canada

19. DCIEM (Defense & Civil Inst. of Environmental Medicine)
Downsview, Ontario, Canada

K. N. Ackles

Switzerland

20. Medical Department
Kantonsspital, Zurich, Switzerland

A. A. Buehlmann

Sweden

21. Lab of Aviation and Naval Physiology
Universite of Lund
Sweden

H. C. Ornhagen

LABORATORIES FORMERLY INVOLVED IN STUDIES RELATED TO HPNS

22. CEMA (Centre de' Etudes Marine Avancees)
Marseille, France

J. Chouteau

USSR

23. Institute of Developmental Physiology
Leningrad, USSR

G. L. Zaltsman

Italy

24. Laboratoire Internationale Medicina
Subacquea, Palermo, Italy

G. Albano

United States

25. Ocean Systems, Inc.
Union Carbide (Linde Div.)
Reston, Virginia

H. Schreiner

IX. PRIORITIES

A list of priorities for research needs can only be taken as a general guide, for as research is carried out or new developments occur, these priorities will change. The list of priorities below must therefore be considered only as a guideline. Further, there is considerable overlap among many of the priorities.

In the Research Needs section of this report, the major priorities are listed, but some small adjustments may be advisable. It is not easy to predict whether advances will be more rapid if human research is given priority over the basic animal studies or vice versa. In fact, both basic and applied research should go hand-in-hand so that each can serve the other.

It is imperative to clarify the nature of HPNS signs and symptoms and stages of onset before adequate attempts can be made to identify the causes and resolve the problems.

Once the taxonomy and signs and symptoms of HPNS have been identified, it is of immediate practical importance to determine the best methods or profiles for compressing men to great depths with little or no HPNS. This may involve testing and applying such factors as selection of personnel, compression profile, accommodation and adaptation, adjustment of temperature, and the use of nitrogen or various anesthetics to modify HPNS. Since all of these methods have some advantage, it is not appropriate to identify any of the above as more meritorious than the rest. A solution to the HPNS problem will probably require that several of these techniques be used at the same time; all deserve urgent study.

Most of the above research is best done in experienced laboratories with suitable wet/dry pressure-chamber facilities.

The next priority therefore would be to attempt to transfer the techniques worked out in pressure chambers to the ocean environment. Finally, work on the possible long-range effects of repeated exposure to HPNS, and the possible residual effects of exposure to a few and many dives should not be neglected. This work needs to be done in both animals and men.

In conjunction with the above research, a proportion of funds must be made available to support the basic animal studies determining the etiology of HPNS, for discovering the etiology will perhaps also suggest other methods of solution. In addition, many of the research opportunities outlined above could use animals to advantage.

APPENDIX A

OFFSHORE WELLS DRILLED IN WATERS EXCEEDING 600 FT SINCE 1965

Operator	Country	Rig Name	Water Depth
1965			
Humble Oil	Southern Calif.	Cuss 1	632
Exxon USA	Santa Barbara Channel	Blue Water 2	629
Exxon USA	Santa Barbara Channel	Blue Water 2	641
Exxon USA	Santa Barbara Channel	Blue Water 2	669
Exxon USA	Santa Barbara Channel	Wodeco 1	994
1969			
Exxon USA	Santa Barbara Channel	Blue Water 2	730
Exxon USA	Santa Barbara Channel	Blue Water 2	941
Exxon USA	Santa Barbara Channel	Blue Water 2	1,005
Exxon USA	Santa Barbara Channel	Wodeco 4	1,046
Exxon USA	Santa Barbara Channel	Wodeco 4	1,245
Exxon USA	Santa Barbara Channel	Wodeco 4	1,299
1970			
Socal-Exxon	Santa Barbara Channel	Wodeco 4	719
Exxon USA	Santa Barbara Channel	Wodeco 4	756
Exxon USA	Santa Barbara Channel	Blue Water 2	762
Exxon USA	Santa Barbara Channel	Wodeco 4	764
Shell Oil	Santa Barbara Channel	Blue Water 2	913
Exxon USA	Santa Barbara Channel	Blue Water 2	1,049
Exxon USA	Santa Barbara Channel	Wodeco 4	1,497

1971

Exxon USA	Santa Barbara Channel	Wodeco 4	812
Exxon USA	Santa Barbara Channel	Wodeco 4	830
Exxon USA	Santa Barbara Channel	Blue Water 2	839
Exxon USA	Santa Barbara Channel	Blue Water 2	849
Exxon USA	Santa Barbara Channel	Wodeco 4	873
Exxon USA	Santa Barbara Channel	Blue Water 2	1,008
Exxon USA	Santa Barbara Channel	Blue Water 2	1,032
Exxon USA	Santa Barbara Channel	Wodeco 4	1,212
Exxon USA	Santa Barbara Channel	Wodeco 4	1,395
Exxon USA	Santa Barbara Channel	Wodeco 4	1,437

1972

Exxon USA	Santa Barbara Channel	Wodeco 4	612
Esso Exploration	Norway	Glomar Grand Isle	635
Shell International	South Korea	Ocean Prospector	646
Socal-Exxon	Santa Barbara Channel	Wodeco 4	768
Exxon USA	Santa Barbara Channel	Wodeco 4	1,070
Shell International	South Java	Sedco 445	1,155
Shell International	South Java	Sedco 445	1,223
Shell International	Brunei	Sedco 445	1,349

1973

Phillips	North Sea	Ocean Rover	616
Shell International	Japan	Ocean Prospector	630
Shell International	Australia	Sedco 445	776
Shell International/AGIP	Adriatic	Scarabeo 2	636
Shell International	Australia	Sedco 445	1,272

Shell International	Brunei	Sedco 445	1,356
1974			
Arco	North Sea	Waage Drill II	612
Shell International	North Sea	Sedco 700	619
British Petroleum	North Sea	Sedco 703	620
Shell International	South Korea	Ocean Prospector	646
British Petroleum	North Sea	Sedco 703	709
Eastcan Exploration	Labrador	Pelican	982
British Petroleum	Newfoundland	Havdrill	1,087
Shell International	Morocco	Sedco 445	1,721
Shell International	Mauritania	Sedco 445	1,929
Shell International	Gabon	Sedco 445	2,097
1975			
Sun	Texas	Sedco 445	2,290
Wapet	West Australia	Century	602
Arco	Louisiana	Dalmahoy	695
Amaco International	East Spain	Mariner II	696
Burmah	Morocco	Sedco I	807
Shell International	Australia	Regional	823
Esso Exploration	Egypt	Endeavor Glomar	829
Shell International	Gabon	Coral Sea	1,200

RIGS DRILLING OVER 3,000 FT.

Drillships

Rig name	Water depth	Owner
UNDER CONSTRUCTION		
Discoveror 534-Seven Seas	6,000	The Offshore Co.
Pelerin	3,281	Helmer Staubo
Sedco 470	6,000	Sedco, Inc.
Unnamed	3,281	Helmer Staubo
U.S. PACIFIC		
Caldrill I	5,000	Marine Drilling

DRILLSHIPS

Rig name	Water depth	Owner
UNDER CONSTRUCTION		
Glomar 40	Unlimited	Exxon
U.S. PACIFIC		
Hughes Glomar Explorer	18,000+	Summa Corp.
MEDITERRANEAN		
Glomar Challenger	Unlimited	Global Marine
AFRICA		
Sedco 445	Unlimited	Sedco, Inc.

RIGS 1,000-3,000 FT ABILITY

Drillships

Rig name	Water depth	Owner
UNDER CONSTRUCTION		
Discoverer IV	1,500	The Offshore Co.
Discoverer 511	1,500	Amoshore
Discoverer 534	3,000	The Offshore Co.
Fredericksburg	1,500	Atwood Oceanics
Glomar Java Sea	1,500	Global Marine
Mission Viking	1,500	Mission Drilling
Unnamed	2,000+	Neddrill
AUSTRALIA		
Regional Endeavour	1,400	Atwood Oceanics
CANADA		
Pelican	1,400	Foramer
MEDITERRANEAN		
Clomar Coral Sea	1,500	Global Marine
Havdrill	1,000+	Nordic Offshore
Saipem Due	1,000+	Saipem SpA
SOUTHEAST ASIA		
Discoverer II	1,500	The Offshore Co.
Western Offshore No. IV	1,500	Fluor Drilling

SEMISUBMERSIBLES

Rig name	Water depth	Owner
UNDER CONSTRUCTION		
Deepsea Saga	1,500	Deep Sea Co.

Ocean Bounty	3,000	Odeco
Ocean Ranger	1,500	Odeco/Fearnley & Eger
Pentagone 91	1,200	Arnt J. Morland
Sedco 707	1,500	Sedco, Inc.
Semi I	1,500	Exxon
Southern Cross	1,500	Santa Fe Int'l.
Unnamed	3,000	Fearnley & Eger
Unnamed	3,000	Fearnley & Eger
Western Pacesetter II	1,200	Western Oceanics
Zapata Lexington	2,000	Zapata Off-Shore
Zapata Saratoga	2,000	Zapata Off-Shore
Zapata Yorktown	2,000	Zapata Off-Shore
LOUISIANA		
Bluewater No. 4	1,500	Santa Fe Int'l.
Zapata 25	2,000	Zapata Off-Shore
MAFLA		
Western Pacesetter III	1,200	Western Oceanics
AUSTRALIA		
Penrod 74	1,000	Penrod Drilling
NORTH SEA		
Dyvi Alpha	2,000	K/S Dyvi Drilling

REFERENCES

1. Albano, G. P., M. Criscuoli, G. C. Scaglione, M. Mazzone, G. Lamonaco, and G. Burmano. 1972. La sindrome da estreme pressioni ambientali. Relievi EEG ed ECG su Ratti Liberi con Electrodi da Dimora. *Ann. Med. Nav. Trop.* 77:11-28.

1a. Bachrach, A. J., and P. B. Bennett. 1973a. The high pressure nervous syndrome during human deep saturation and excursion diving. *Foervarsmedicin* 9:490-495.

2. Bachrach, A. J., and P. B. Bennett. 1973b. Tremor in diving. *Aerospace Med.* 44:613-623.

3. Bachrach, A. J., D. R. Thorne, and K. J. Conda. 1971. Measurement of tremor in the Makai Range 520-foot saturation dive. *Aerospace Med.* 42:856-860.

4. Barthelemy, L., A. Belaud, M. Bellet, and C. Payraud. 1971. Etude, chex le poisson, des effets de la pression soit en tant que force appliquee, sort associee a une augmentation de la masse des gas dissours. (Study, in fish, of the effect of pressure either as an applied force, or associated with an increase in mass of dissolved gases.) *Compt. Rend. Soc. Biol.* 165:1754-1756.

5. Barthelemy, L., and A. Belaud. 1972. Constatations physiologiques et physiopathologiques faites sur un poisson (Anguilla anguilla L.) en conditions hyperbares. *Bull. Medsubhyp Rept. 8*, Service d'Hyperbare, Hospital Salvator, Marseille.

6. Bean, J. W. 1950. Tensional changes of alveolar gas in reactions to rapid compression and decompression and question of nitrogen narcosis. *Am. J. Physiol.* 161:417

7. Becker, R. W. 1972. Pressure effects on the properties of high molecular weight substances in solution. In: *Barobiology and the Experimental Biology of the Deep Sea*, edited by R. Brauer. Special Publication, North Carolina Sea Grant Program, North Carolina.

8. Bennett, P. B. 1965. Psychometric impairment in men breathing oxygen/helium at increased pressures. *Med. Res. Council, UK Roy. Nav. Pers. Res. Comm., Underwater Physiol. Rept. 251.*

9. Bennett, P. B. 1964. The effects of high pressures of inert gases on auditory evoked potentials in cat cortex and reticular formation. *Electroencephalog. Clin. Neurophysiol.* 17:388-397.

10. Bennett, P. B. 1965a. The action of inert gases of hyperpressure. In: *Proc. 2nd Intern. Symp. Underwater Med., Mondo Sommerso* 7. Palermo, Italy: Ustica.

11. Bennett, P. B. 1965b. Cortical CO_2 and O_2 at high pressures of argon, nitrogen, helium, and oxygen. *J. Appl. Physiol.* 20:1249-1252.

12. Bennett, P. B. 1966. *The Aetiology of Compressed Air Intoxication and Inert Gas Narcosis.* Oxford: Pergamon.

13. Bennett, P. B. 1967. Performance impairment in deep diving due to nitrogen, helium, neon and oxygen. In: *Proc. 3rd Symp. Underwater Physiol*, edited by C. J. Lambertsen. Baltimore: Williams and Wilkins.

14. Bennett, P. B. 1970. Pressure physiology. Interim report on some physiological studies during 1500-foot simulated dive. UK Roy. Nav. Physiol. Lab. Rept. IR 1/70.

15. Bennett, P. B. 1971a. Changes in human physiology during simulated oxygen-helium exposures between 100 ft and 1500 ft. UK Roy. Nav. Physiol. Lab. Final Report.

15a. Bennett, P. B. 1971b. Neurophysiological, psychological, biochemical and other physiological studies. In: Experimental observations on men at pressures between 4 bar (100 ft) and 47 bars (1,500 ft). UK Roy. Nav. Physiol. Lab. Rept. 1/71.

16. Bennett, P. B., and A. N. Dossett. 1967. Undesirable effects of oxygen-helium at great depths. Med. Res. Council, UK Roy. Nav. Pers. Res. Comm. Underwater Physiol. Rept. 260.

17. Bennett, P. B., and A. N. Dossett. 1973. EEG activity of rats compressed by inert gases to 700 feet and oxygen-helium to 4000 feet. Aerospace Med. 44:239-244.

17a. Bennett, P. B., and E. J. Towse. 1971a. Performance efficiency of men breathing oxygen-helium at depths between 100 feet and 1,500 feet. Aerospace Med. 42:1147-1156.

17b. Bennett, P. B., and E. J. Towse. 1971b. The high pressure nervous syndrome during a simulated oxygen-helium dive to 1,500 ft. Electroencephalog. Clin. Neurophysiol. 31:383-393.

17c. Bennett, P. B., and E. J. Towse. 1972. Electroencephalogram, tremors and mental performance during exposure to air or oxygen-helium at 100 ft., 200 ft. and 300 ft. UK Roy. Nav. Physiol. Lab. Rept. 3/72.

17d. Bennett, P. B., G. D. Blenkarn, J. Roby, and D. Youngblood. 1974. Suppression of the high pressure nervous syndrome in human deep dives by He-N_2-O_2. Undersea Biomed. Res. 1:221-237.

17e. Bennett, P. B., J. Roby, S. Simon, and D. Youngblood. 1975. Optimal use of nitrogen to suppress the high pressure nervous syndrome. Aviat. Space Environ. Med. 46:37-40.

18. Bennett, P. B., and S. P. Gray. 1971. Changes in human urine and blood chemistry during a simulated oxygen-helium dive to 1500 ft. Aerospace Med. 42:868-874.

19. Bennett, P. B., D. Papahadjopoulos, and A. D. Bangham. 1967. The effect of raised pressures of inert gases on phospholipid model membranes. Life Sci. 6:2527-2533.

20. Bennett, P. B., J. B. Morrison, E. E. P. Barnard, and J. Eaton. 1971. Experimental observations on men at pressures between 4 bars (100 ft.) and 47 bars (1500 ft.) UK Roy. Nav. Physiol. Lab. Rept. 1/71.

21. Biersner, R. J. 1971. Human performance at great depths. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen, New York: Academic Press.

22. Biersner, R. J., and B. J. Cameron. 1970a. Memory impairment during a deep helium dive. Aerospace Med. 41:658-661.

23. Biersner, R. J., and B. J. Cameron. 1970b. Cognitive performance during a 1000-ft helium dive. Aerospace Med. 41:928-930.

24. Bornmann, R. C. 1971. Helium-oxygen saturation-excursion diving for the U.S. Navy. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. New York: Academic Press.

25. Brauer, R. W. 1968. Seeking man's depth level. Ocean Industry 3:28-33.

25a. Brauer, R. W. 1970. Human performance in high pressure inert gas environments. In: Undersea Technology Handbook and Directory. Arlington, Va.: Compass.

26. Brauer, R. W. (Ed.) 1972. Barobiology and the Experimental Biology of the Deep Sea. North Carolina: Special Publication, North Carolina Sea.

27. Brauer, R. W., D. O. Johnsen, R. L. Pessotti, and R. W. Redding. 1966. Effects of hydrogen and helium at pressures to 67 atmospheres on mice and monkeys. Fed. Proc. 25:202.

27a. Brauer, R. W., M. R. Jordan, and R. O. Way. 1968. Modification of the convulsive seizure phase of the high pressure excitability syndrome in mice. Fed. Proc. 27:284.

28. Brauer, R. W., M. R. Jordan, and R. O. Way. 1972. The high pressure neurological syndrome in the squirrel monkey. Saimiri sciuress. In: Proc. 3rd Intern. Conf. Hyperbaric Underwater Physiol., edited by X. Fructus. Paris: Doin.

29. Brauer, R. W., M. R. Jordan, R. W. Beaver, and S. M. Goldman. (in press). Interaction of the high pressure neurological syndrome with various pharmacological agents. In: Proc. 5th Symp. Underwater Physiol., edited by S. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

30. Brauer, R. W., R. O. Way, and M. R. Jordan. 1971. Experimental studies on the high pressure neurological syndrome in various mammalian species. In: Proc. 4th Symp. Underwater Physiol., edited by C. J. Lambertsen. New York and London: Academic Press.

31. Brauer, R. W., R. O. Way, M. R. Jordan, and D. E. Parrish. 1970. Effects on squirrel monkeys of sojourns of 2-24 hours in helium or hydrogen-oxygen atmospheres at pressures of 50-80 atm. Fed. Proc. 29:594.

32. Brauer, R. W., R. O. Way, M. R. Jordan, D. E. Parrish, R. W. Beaver, and S. M. Goldman. 1974. Repeated exposure to high pressure heliox atmospheres. Undersea Biomed. Res. 1:239-250.

32a. Brauer, R. W., R. O. Way, and R. A. Perry. 1968. Narcotic effects of helium and hydrogen in mice and hyperexcitability phenomena at simulated depths of 1,500 to 4,000 feet of sea water. In: Toxicity of Anesthetics, edited by B. R. Fink. Baltimore: Williams and Wilkins.

33. Brauer, R. W., R. W. Beaver, and W. M. Mansfield. 1974. Compression rate effects upon HPNS and the question of etiology. (Abstract). Undersea Biomed. Res. 1:A34.

34. Brauer, R. W., S. Dimov, X. Fructus, A. Gosset, and R. Naquet. 1969. Syndrome neurologique et electrographique des hautes pressions. Revue Neurol. 121:264-265.

35. Brouha, A., A. Pegneux, E. Schoffeniels, and A. Disteche. 1970. The effects of high hydrostatic pressures on the permeability characteristics of the isolated frog skin. Biochim. biophys. Acta 219:455-462.

36. Brumlik, J. 1962. On the nature of normal tremor. Neurol. 12:159-179.

37. Brumlik, J., and C. B. Yap. 1970. Normal Tremor: A Comparative Study. Springfield, Ill.: Thomas.

38. Buehlmann, A. A., H. Matthys, G. Overrath, P. B. Bennett, D. H. Elliott, and S. P. Gray. 1970. Saturation exposures of 31 ats in an oxygen-helium atmosphere with excursions to 36 ats. *Aerospace Med*. 41:394-402.

39. Carpenter, F. G. 1953. Anesthetic action of inert and unreactive gases on intact animals and isolated tissues. *Am*. *J*. *Physiol*., 178:505-509.

40. Chouteau, J. A., G. Imbert, and J. Alinat. 1969. Sur une meilleure definition des phenomensphypoxiques accompagnant la respiration du melange oxygene-helium au cours des plonges profondes a saturation. *Compt*. *Rend*. 268:2918-2921.

40a. Chouteau, J., G. Imbert, and J. C. LePechon. 1972. Physiologie comparee de divers mammiferes aux hautes pressions en atmosphere oxygen-helium. (Comparative physiology of various mammals at high pressure in oxygen-helium atmosphere.) *Maroc*. *Med*. 52:448-449.

41. Chouteau, J., and G. Imbert. 1971. La limitation hypoxique de la plongee profonde de longue duree. *Maroc*. *Med*. 52:229-236.

41a. Chouteau, J., J. M. Ocana de Sentuary, and L. Pironti. 1971. A comparative and theoretical study of compression rate in deep diving. In: *Abstracts of the 25th Congress of Physiological Sciences Satellite Symposium*. Marseille, France, July, 1971. (Proceedings unpublished).

42. Chouteau, J. A., Y. Cousteau, J. Alinat, and C. F. Aquadro. 1968. Sur les limites physiologiques de la plongee a saturation a l'air et aux melanges synthetiques. *Rev*. *Subaq*. *Physiol*. 1:38-44.

43. Cromer, J. A., W. L. Hunter, and P. B. Bennett. (in preparation). Effects of temperature on the High Pressure Nervous Syndrome (HPNS) in rats. In: *Proc*. *6th Symp*. *Underwater Physiol*., edited by C. J. Lambertsen.

44. COMEX: 1970 *New World Record Simulated Deep Dive*. (Physalie V. experiment.) Hyperbaric Research Center, COMEX, Marseilles.

45. Disteche, A. 1972. Electrochemical devices for in situ or simulated deep sea measurements. *Barobiology and the Experimental Biology of the Deep Sea*, edited by R. Brauer. North Carolina: Special Publication, North Carolina Sea Grant Program.

46. Doebbler, G. F., H. H. Bruemmer, and H. R. Schreiner. 1967. Influences of high pressures of inert gases upon cell activity. In: *Proc*. *3rd Symp*. *Underwater Physiol*., edited by C. J. Lambertsen. Baltimore: Williams and Wilkins.

47. Dossett, A. N., and V. Hempleman. 1972. The importance for mammals of rate of compression. (Symp. on Effects of Pressure on Organisms). *Proc*. *Soc*. *Exp*. *Biol*. 26:355-361.

48. Dreher, J. J., and A. J. Bachrach. 1969. Power spectral density: a methodology for the rhythm analysis of disordered speech. In: *Schizophrenia*: *Current Concepts and Research*, edited by D. V. Siva Sankar. New York: PJD Publications.

49. Ebbecke, U. 1914. Wirkung allseitigen Kompression auf den Froschmuskel. *Pfluegers Arch*. *ges*. *Physiol*. 157:75-116.

50. Ebbecke, U., and Hasenring. 1935. Ueber die Kompressionbekuerzung des Muskels bei Einwirkung hoher Drucke. *Pfluegers Arch*. *ges*. *Physiol*. 236:405-415.

51. Ebbecke, U., and H. Schaefer. 1935. Ueber den Einfluss hoher Drucke auf den Aktionsstrom von Muskeln and Nerven. *Pfluegers Arch. ges. Physiol*. 236:678-692.

52. Enns, T., P. F. Scholander, and E. D. Bradstreet. 1965. Effect of hydrostatic pressure on gases dissolved in water. *J. Phys. Chem*. 69:389-391.

53. Featherstone, R. M., S. Hegeman, and W. Settle. 1971. Effects of inert gas pressures on protein structure and function. In: *Proc. 4th Symp. Underwater Physiol*., edited by C. J. Lambertsen. New York: Academic Press.

54. Feldberg, N. 1968. The monoamines of the hypothalamus as mediators of temperature responses. In: *Recent Advances in Pharmacology*, edited by J. M. Robson and R. S. Stacey. London: Churchill.

55. Fenn, W. O. 1967. The possible role of hydrostatic pressure in diving. In: *Proc. 3rd Symp. Underwater Physiol*., edited by C. J. Lambertsen. Baltimore: Williams and Wilkins.

56. Fenn, W. O. 1969. The physiological effects of hydrostatic pressure. In: *The Physiology and Medicine of Diving and Compressed Air Work*, edited by P. B. Bennett and D. H. Elliott. Baltimore: Williams and Wilkins.

57. Flugel, H. 1972. Adaptation and acclimatization to high pressure environments. In: *Barobiology and the Experimental Biology of the Deep Sea*, edited by R. Brauer. North Carolina: Special Publication, North Carolina Sea Grant Program.

58. Fontaine, M. 1930. Recherches experimentales sur les reactions des etres vivants aux fortes pressions. *Ann. Inst. Oceanog. Monaco* 8:5-97.

58a. Fructus, X., and C. Agarate. 1971. The high pressure nervous syndrome. *Med. Sport* 24:272-278.

59. Fructus, X., and J. C. Rostain. (in preparation). HPNS: A clinical study of 30 cases. In: *Proc. 6th Symp. Underwater Physiol*., edited by C. J. Lambertsen.

59a. Fructus, X., and J. P. Charpy. 1972. Etude psychometrique de 2 subjet lors d'une plongee fictive jusqu'a 52.42 ATA. (Psychometric study of 2 subjects during a simulated dive to 52.42 ATA.) *Bull. Medsubhyp*. 7:3-12.

59b. Fructus, X., and J. Vigreux. 1970. Les plongees tres profondes--point des resultat acquis. (Dives at great depths--data acquired.) *Bull. Medsubhyp* 2:23-25.

59c. Fructus, X., and V. Conti. 1971. Le syndrome nerveux des hautes pressions. (The high pressure nervous syndrome.) In: *Medecine de Plongee*, edited by J. R. L'Huillier. *Gaz. Hop*. 35:1031-1036.

60. Fructus, X., C. Agarate, and F. Sicardi. (in press). Postponing the high pressure nervous syndrome (HPNS) down to 500 meters and deeper. Study of compression rates for very deep dives. In: *Proc. 5th Symp. Underwater Physiol*., edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

61. Fructus, X., D. Agarate, R. Naquet, and J. C. Rostain. (in press). Postponing the "High Pressure Nervous Syndrome" (H.P.N.S.) to 1640 feet and beyond. In: *Proc. 5th Symp. Underwater Physiol*., edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

62. Fructus, X. R. (Ed.). 1972. Down below the great depths. In: *Proc. 3rd Intern. Conf. on Hyperbaric and Underwater Physiol*. Paris: Doin.

62a. Fructus, X., R. Naquet, A. Gosset, P. Fructus, and R. W. Brauer. 1969. Le syndrome nerveux des hautes pressions. (The high pressure nervous syndrome.) *Marseille Med*. 106:509-512.

63. Fructus, R. X., R. W. Brauer, and R. Naquet. 1971. Physiological effects observed with course of simulated deep chamber dives to a maximum of 36.5 atmospheres in helium-oxygen atmosphere. In: *Proc. 4th Symp. Underwater Physiol*., edited by C. J. Lambertsen. New York: Academic Press.

64. Gerber, B. R., and H. Noguchi. 1967. Volume changes associated with the G-F transformation of flagellin. *J. Mol. Biol*. 26:197-210.

65. Gershfeld, N. T., and A. M. Shanes. 1959. The influence of high hydrostatic pressure on cocaine and veratrine action in a vertebrate nerve. *J. Gen. Physiol*. 42:647-653.

66. Goffart, M. 1968. The problem of slothfulness in the didactyl sloth (Choloepus hoffmanni Pet.) *Electromyography* 8:245-251.

67. Gottlieb, S. F., G. J. Koehler, and L. V. G. Rhodes. (in press). A pressure-sensitive enzyme: adenosinetriphosphatase. In: *Proc. 5th Symp. Underwater Physiol*., edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

68. Grundfest, H. 1936. Effects of hydrostatic pressures on the excitability, the recovery and the potential sequence of frog nerve. *Cold Spring Harbor Symp. Quant. Biol*. 4:179-187.

69. Grundfest, H., and M. Cattell. 1935. Some effects of hydrostatic pressure on nerve action potentials. *Am. J. Physiol*. 113:56-57.

70. Halsey, M. J., D. W. Kent, and E. I. Eger, II. (in press). Pressure studies with mice up to 270 ATA. In: *5th Symp. Underwater Physiol*., edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

71. Hamilton, R. W., Jr. (in press). Psychomotor performance in normoxic neon and helium at 37 atmospheres. In: *5th Symp. Underwater Physiol*., edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

72. Hamilton, R. W., Jr., J. B. MacInnis, A. D. Noble, and H. R. Schreiner. 1967. Saturation diving at 650 feet. *Tech. Memo. B 1 411*. Ocean Systems, Inc., Tonawanda, New York.

73. Hawkins, I. K. 1972. Helium effect on cardiac mitochondria of mice. *Aerospace Med*. 43:775-777.

74. Hawkins, I. K. 1973. Helium effect on skeletal muscle of mice. *Aerospace Med*. 43:374-378.

75. Henry, K. R. 1967. Acoustic priming of audiogenic seizures in a previously non-susceptible strain of mice. *Science* 158:938-939.

76. Hills, B. A. 1971. Gas-induced osmosis as a factor influencing the distribution of body water. *Clin. Sci*. 40:175-191.

77. Horne, R. W., and B. A. Courant. 1972. Pressure-induced changes in aqueous solutions and their possible significance. In: *Barobiology and the Experimental Biology of the Deep Sea*, edited by R. Brauer. North Carolina: Special Publication, North Carolina Sea Grant Program.

78. Hu, J. H., and F. Russo. (in press). The effects of helium and oxygen mixtures on wakeful and sleeping human electroencephalography and other physiological functions at normal atmospheric pressure. In: *Proc. 5th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

79. Hurd, R., R. W. Brauer, and B. J. Wilder. (in press). Convulsions and tremorigenie phenomena associated with high pressure neurologic syndrome. *Trans. Am. Neurol. Assoc.*

80. Jarrett, A. S. 1966. Alveolar carbon dioxide tension at increased ambient pressure. *J. Appl. Physiol.* 21:158-162.

81. Johnson, F. H., and H. Eyring. 1970. The kinetic basis of pressure effects in biology and chemistry. In: *High Pressure Effects on Cellular Processes*, edited by A. M. Zimmerman. New York: Academic Press.

82. Johnson, F. H., H. Eyring, and M. F. Polissar. 1954. *The Kinetic Basis of Molecular Biology*. New York: John Wiley.

83. Josephs, R., and W. F. Harrington. 1968. On the stability of myosin filaments. *Biochemistry* 7:2834-2847.

84. Kitching, J. A. 1957. Effects of high hydrostatic pressures on the activity of flagellates and ciliates. *J. Exp. Biol.* 34:494-510.

85. Kleinholz, L. H. 1938. Studies in reptilian color changes II. The pituitary and adrenal glands in the regulation of the melanophores of Anolis carolnensis. *J. Exp. Biol.* 15:474-491.

86. Krasberg, A. R. 1967. Saturation diving: vertical excursion techniques. In: *The New Thrust Seaward*. Washington: Marine Technology Society.

87. Kylstra, J. A., I. S. Longmuir, and M. Grace. 1968. Dysbarism: osmosis caused by dissolved gas? *Science* 161:289.

88. Kylstra, J. A., R. Nantz, J. Crowe, W. Wagner, and H. A. Saltzman. 1967. Hydraulic compression of mice to 166 atmospheres. *Science* 158:793-794.

89. Laidler, K. J., and A. J. Beardell. 1955. Molecular kinetics of adenoisinetriphosphatase. III. Influence of hydrostatic pressure. *Arch. Biochem. Biophys.* 55:138-151.

90. Lambertsen, C. J. (Ed.). (in press). Collaborative investigation of limits of human tolerance to pressurization with helium, neon and nitrogen. Simulation of density equivalent to helium-oxygen respiration at depths to 2000, 3000, 4000, and 5000 ft. of sea water. In: *Proc. 5th Symp. Underwater Physiol.* Washington, D.C.: Fed. Am. Soc. Exp. Biol.

91. Landau, J. V. 1970. Hydrostatic pressure on the biosynthesis of macromolecules. In: *High Pressure Effects on Cellular Processes*, edited by A. M. Zimmerman. New York: Academic Press.

92. Landau, J. V. 1971. Hydrostatic effects on cellular function. In: *Proc. 4th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. New York: Academic Press.

93. Langley, T. D. 1969. Report of steadiness tests conducted on OSE Dive No. 44. *Tech. Memo.* Ocean Systems, Inc., Tonawanda, New York.

94. Langley, T. D. (in press). Somatic and auditory evoked responses in man breathing mixtures of normoxic helium nitrogen and neon at pressures to 37 atmospheres. In: *Proc. 5th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

95. Leon, H. A., and S. F. Cook. 1960. A mechanism by which helium increases metabolism in small mammals. *Am. J. Physiol.* 199:243-245.
96. Lever, M. J., K. W. Miller, W. D. M. Paton, and E. B. Smith. 1971. Pressure reversal in anesthesia. *Nature* 231:371-386.
97. Lever, M. J., K. W. Miller, W. D. M. Paton, W. B. Street, and E. B. Smith. 1971. Effects of hydrostatic pressure on mammals. In: *Proc. 4th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. New York: Academic Press.
98. Lippold, O. 1971. Physiological tremor. *Sci. Am.* 224:65-73.
99. Lippold, O. C. J., J. W. T. Redfearn, and J. Vuco. 1958. The frequency spectrum of the muscular activity of shivering in the anesthetized cat. *J. Physiol.* 140:49.
100. Lucien, C., and M. Barthelemy. 1970. *Contribution to a Study on Inert Gases, Narcosis and the High Pressure Syndrome*. (Diplome D'Etudes Superieres, Feb. 1970.) (NAVSHIPS Transl. 1263, Feb. 1971), Sci. Doc. Div. (205), Naval Ships Systems Command, Washington, D.C.
101. Lundgren, C., and H. Ornhagen. (in press). Hydrostatic pressure tolerance in liquid breathing mice. In: *Proc. 5th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.
102. Macdonald, A. G. (in press) Locomotor activity and oxygen consumption in shallow and deep sea invertebrates exposed to high hydrostatic pressure and low temperature. In: *Proc. 5th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.
103. MacDonald, A. G. 1967. The effect of high hydrostatic pressure on the cell division and growth of Tetrahymena pyriformis. *Exp. Cell Res.* 47:569-580.
104. MacDonald, A. G. 1972. The role of high hydrostatic pressure in the physiology of marine animals. *Symp. Soc. Exp. Biol.* 26:209-231.
105. MacInnis, J. B. 1969. Some comparisons of U.S. Navy and civilian diving programs. *Progress in the sea: Trans. Symp.* Washington: Marine Technology Society.
105a. MacInnis, J. B., J. G. Dickson, and C. J. Lambertsen. 1967. Exposure of mice to a helium-oxygen atmosphere at pressures to 122 atmospheres. *J. Appl. Physiol.* 22:694-698.
105b. Mansfield, W. M., R. W. Brauer, and H. W. Gillen. 1974. Age dependence of seizure patterns in mice exposed to high pressure heliox atmospheres. *Fed. Proc.* 33:350.
106. Marsland, D. 1970. Pressure temperature studies on the mechanism of cell division. In: *High Pressure Effects on Cellular Processes*, edited by A. M. Zimmerman. New York: Academic Press.
107. Marsland, D. A. 1958. Cells at high pressures. *Sci. Am.* 199:36-43.
108. Membery, J. H., and E. A. Link. 1964. Hyperbaric exposure of mice to pressures of 60-90 atmospheres. *Science* 144:1241-1242.
109. Michaud, A., J. Parc, J. Lechuiton, L. Barthelemy, G. Balouet, E. Girin, J. Corriol, and J. Chouteau. Deep dive with hydrogen-oxygen mixtures. G.E.R.S. experiments on rabbits and white rats. In: *Proc. 5th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

110. Michaud, A., J. Parc, L. Barthelemy, J. Lechuiton, J. Corroll, J. Chouteau, and F. Leboucher. 1969. Premieres donnees sur une limitation de l'utilizztion de melange oxygene-hydrogene pour la plongee profounde a saturation. Compt. Rend. 269:497-499.

110a. Miller, K. W., W. D. M. Paton, E. B. Smith, and R. A. Smith (in press). Pressure reversal and the mechanism of general anesthesia. In: Proc. Fifth Symp. Underwater Physiol., edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

111. Miller, K. W., W. D. M. Paton, R. A. Smith, and E. B. Smith. 1973. The pressure reversal of general anesthesia and the critical volume hypothesis. Mol. Pharmacol. 9:131-143.

112. Miller, K. W., W. D. M. Paton, W. B. Street, and E. B. Smith. 1967. Animals at very high pressures of helium and neon. Science 157: 97-98.

113. Morita, R. Y., and R. R. Becker. 1970. Hydrostatic pressure effects on selected biological systems. In: High Pressure Effects on Cellular Processes, edited by A. M. Zimmerman. New York: Academic Press.

114. Morrison, J. B., and J. T. Florio. 1971. Respiratory function during a simulated dive to 1500 ft. J. Appl. Physiol. 30:724-732.

115. Murayama, M. 1966. Molecular mechanism of red cell sickling. Science 153:145-149.

116. Murayama, M., and F. Hasegawa. 1970. Effect of hydrostatic pressure on the aggregation reaction of human fibrin at 23°C. Fed. Proc. 29:874.

117. Naquet, R., J. C. Rostain, and X. Fructus. 1975. High pressure nervous syndrome: Clinical and electrophysiological studies in man. In: Strategy for Future Diving to Depths Greater than 1000 Feet. UMS Report WS G-15-75.

118. Ornhagen, H. C., and C. E. G. Lundgren. (in press). Hydrostatic pressure tolerance in liquid-breathing mice. In: Proc. 5th Symp. Underwater Physiol., edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

119. Overfield, E. M., H. A. Saltzman, J. A. Kylstra, and J. V. Salzano. 1969. Respiratory gas exchange in normal men breathing 0.9% oxygen in helium at 31.3 ATA. J. Appl. Physiol. 27:471-475.

120. Parker, J. W. 1969. Performance effects of increased ambient pressure. II. Helium-oxygen saturation and excursion dive to a simulated depth of 1100 ft. Rept. 596, U.S. Naval Submarine Medical Center, Groton, Conn.

121. Paton, W. D. M. 1967. Experiments on the convulsant effects of oxygen. Brit. J. Pharmacol. 29:350-366.

122. Podolsky, R. J. 1956. A mechanism for the effect of hydrostatic pressure on biological systems. J. Physiol., London 132:38-39.

123. Proctor, L. D., C. R. Carey, R. M. Lee, K. E. Schaefer, and H. van den Ende. 1972. Electroencephalographic changes during saturation excursion dives to a simulated sea water depth of 1000 ft. Aerospace Med. 43:867-877.

124. Rahn, H. 1956. The relationship between hypoxia, temperature, adrenalin release and melanophore expansion in the lizard Anolis Carolinensis. Copeia, p. 214-217.

125. Rashbass, C. 1955. The unimportance of carbon dioxide as a cause of nitrogen narcosis. *Med. Res. Council Rept., UK Roy. Nav. Pers. Res. Comm.*

126. Raymond, L. W., and W. H. Spaur. 1974. Biomedical research and underwater breathing apparatus evaluation dives 10 to 1600 ft. (Abstracts). *Nav. Med. Res. Inst. Exp. Diving Unit. Joint Tech. Rept.*

127. Regnard, P. 1891. Influence de la pression sur la vie aquatique. In: *La Vie dans les Eaux*, edited by P. Regnard. Paris: Masson.

128. Ritter, R., R. Vandrovec, and R. H. Wilson. 1969. Gamma aminobutyric acid levels in brains of mice exposed to 20, 40, and 60 atmospheres He-O_2 for 24 hours. *Aerospace Med*. 40:994-997.

129. Roger, A., P. Cabarrou, and H. Gastaut. 1955. EEG changes in humans due to changes in surrounding pressure. *Electroencephalog. Clin. Neurophysiol*. 7:1.

130. Rostain, J. C. 1973. *L'effet des hautes Pressions avec Divers melanges Gazeux chez le singe Papio papio*. These de Doctorat de Specialite en Neurophysiologie, Universite de Provence, 131.

131. Rostain, J. C., and A. Regesta (in press). Evolution dusommeil de plongeurs au cours d'un sejour prolonge sous une pressure de 31 atm de melange helium-oxygene. *Revue Electroencephalog. Neurophysiol*.

131a. Rostain, J. C., and C. Lemaire. 1973. Evolution du tremblment au repos et pendant l'effort au cours de plongees profondes en atmosphere helium-oxygene. (Evolution of tremor at rest and during exertion during deep dives in a helium-oxygen breathing mixture.) *Rev. Electroencephalog. Paris* 3:203-206.

131b. Rostain, J. C., C. Lemaire, and C. Agarate. 1973. Physiological results of experimental dives down to 610 meters with human subjects. In: *Proc. World Confed. Underwater Activity*, London.

131c. Rostain, J. C., and R. Naquet. 1972. Resultats preliminaires d'une etude comparative de l'effet des melanges oxygene-helium et oxygene-hydrogene et des hautes pressions sur le babouin Papio-papio. In: *Proc. 3rd Intern. Conf. Hyperbaric and Underwater Physiol.*, edited by X. Fructus. Paris: Doin.

132. Rostain, J. C., and R. Naquet. 1974. Le syndrome nerveux des hautes pressions: caracteristiques et evolution en fonction de divers modes de compression. *Rev. Electroencephalog. Neurophysiol*. 4:107-124.

133. Rostain, J. C. and R. Naquet. (in preparation). Human neurophysiological data obtained from two simulated heliox dives to a depth of 610 meters. In: *Proc. 6th Symp. Underwater Physiol.*, edited by C. J. Lambertsen.

134. Rostain, J. C., X. Fructus, and R. Naquet. 1970. Etude preliminaire de l'effect des hautes pressions en atmosphere helium-oxygene sur le singe Papio papio. *Rev. Neurol*. 122:482-483.

135. Rucci, F. S., M. L. Giretti, and M. Larocca. 1968. Cerebellum and hyperbaric oxygen. *Electroencephalog. Clin. Neurophysiol*. 25:359-371.

136. Salzano, J. V., D. C. Rausch, and H. A. Saltzman. 1970. Cardiorespiratory responses to exercises at a simulated seawater depth of 1000 feet. *J. Appl. Physiol*. 28:34-41.

137. Schaefer, K. E., C. R. Carey, and J. Dougherty. 1970. Pulmonary gas exchange and urinary electrolyte excretion during saturation excursion diving to pressures equivalent to 800 and 1000 feet of seawater. *Aerospace Med*. 41:856-864.

138. Schaefer, K. E., G. F. Bond, W. F. Mazzone, C. R. Carey, and J. H. Dougherty. 1968. Carbon dioxide retention and metabolic changes during prolonged exposure to a high pressure environment. *Aerospace Med*. 39:1206-1215.

139. Schreiner, H. R., R. C. Gregoire, and J. A. Lawrie. 1962. A new biological effect of the gases of the helium group. *Science* 136:653-654.

140. Sheehan, M. E., and R. W. Bauer. 1974. Temperature regulation and energy balance in mice under high pressures. In: *2nd Symp. Pharmacol. Thermoregulation II*. Paris.

141. Sleigh, M. A., and A. G. MacDonald. 1972. *The Effects of Pressure on Organisms: A Symposium of the Society for Experimental Biology*. New York: Academic Press.

142. South, F. E., Jr., and S. F. Cook. 1953. Effect of helium on the respiration and glycolysis of mouse liver slices. *J. Gen. Physiol*. 36:513-528.

143. Spyropoulos, C. S. 1957b. Response of single nerve fibers at different hydrostatic pressures. *Am. J. Physiol*. 189:214-218.

144. Spyropoulos, C. S. 1957a. The effects of hydrostatic pressure on the normal and narcotized nerve fiber. *J. Gen. Physiol*. 40:849-857.

145. Summit, J. K., J. S. Kelley, J. M. Herron, and H. A. Saltzman. 1969. Joint U.S. Navy-Duke University 1000-foot saturation dive. U.S. Navy Experimental Diving Unit. *Rept. 3-69*.

146. Suzuki, K., and Y. Taniguchi. 1972. Effect of pressure on biopolymers and model system. *Symp. Soc. Exp. Biol*. 26:103-124.

147. Varene, P., G. G. Saumon, A. Viellefond, and J. L'Huiller. 1971. Mecanique ventilatoire en plongee profounde-resultats de l'experience PHYSALIE V. *Bull. Medsubhyp*. 6: 9-16.

148. Vigreux, J. 1970. Contribution to the study of the neurological and mental reactions of the organism of the high mammal to gaseous mixtures under pressure. *M.D. Thesis*. Toulouse University, France.

149. Wood, J. 1969. Oxygen toxicity. In: *The Physiology and Medicine of Diving and Compressed Air Work*, edited by P. B. Bennett and D. H. Elliott. Baltimore: Williams and Wilkins.

150. Wright, W. B., and R. Peterson. (in press). Pulmonary mechanical functions in man breathing dense gas mixtures. In: *Proc. 5th Symp. Underwater Physiol.*, edited by C. J. Lambertsen. Washington, D.C.: Fed. Am. Soc. Exp. Biol.

151. Wyatt, R. H., Jr. 1968. A study of power spectra analysis of normal finger tremors. *IEEE Trans. Bio-med. Eng*. 15:33-45.

152. Zaltsman, G. L. (Ed.). 1968. *Giperbaricheskiye epilepsiya i narkoz*. Leningrad: USSR Academy Science.

153. Zaltsman, G. L. (Ed.). 1968. *Hyperbaric Epilepsy and Narcosis (Neurophysiological Studies)*. Leningrad: Sechenov Institute of Evolutionary Physiology and Biochemistry, USSR Academy of Sciences.

154. Zaltsman, G. L. 1961. Physiological principles of a sojourn of a human in conditions of raised pressure of the gaseous medium. (English translation by Foreign Technology Div., Wright-Patterson AFB, Ohio, 1967.)

155. Zaltsman, G. L., A. I. Selivra, and V. P. Ponomaryer. 1973. Sinchronizatsiya biopotentsialov mozga pri generalizatsii patologicheskovo vozbushdyenniya i tormozhenniya. In: *Symposium*: *Problemi prostranstvennoi sinchronizatsii biotentsialov golovnovo mozga*, edited by M. N. Livanov. Pushkino: Akademiva Nauk USSR.

157. Zimmerman, A. M. (Ed.). 1970. *High Pressure Effects on Cellular Processes*. New York: Academic Press.

158. Zimmerman, A. M. 1971. High pressure studies on cell biology. *Intern. Rev. Cytol.* 30:1-47.

159. Zimmerman, S. B., and A. M. Zimmerman. 1970. Biostructural cytokinetic and biochemical aspects of hydrostatic pressure effects on protozoa. In: *High Pressure Effects on Organisms*. New York: Academic Press.

160. Zobell, C. E., and J. Kim. 1972. Effects of deep-sea pressures on marine microbial enzyme systems. *Symp. Soc. Exp. Biol.* 26:125-146.

Addendum

Hunter, W. L., Jr., and P. B. Bennett. 1974. Causes, mechanisms, and prevention of the high pressure nervous syndrome. *Undersea Biomed. Res.* 1:1-28.

MICROBIOLOGICAL ASPECTS

Part #13 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Andre B. Cobet, Ph.D., LCDR, MSC, USN (Chairman)
Executive Officer
Naval Biomedical Research Laboratory
Oakland, California

M. Mazzarella, CAPT., DC, USN
Naval Regional Dental Center
Norfolk, Virginia

Ernest V. Orsi, Ph.D.
Professor, Biology Department
Seton Hall University
South Orange, New Jersey

N. A. Schlamm, CAPT., MSC, USN
Naval Medical Research and Development Command
Bethesda, Maryland

TABLE OF CONTENTS and Organization for part 13

I. INTRODUCTION 1

II. MICROBIAL PHYSIOLOGY 1

A. Recommended Research

III. HYPERBARIC OXYGEN AND VIRUS INFECTION 4

A. Enhanced Virus

B. Recommended Research

1. Cell Culture Studies
2. Animal Experimentation
3. Human Studies

IV. IMMUNOLOGIC CONSIDERATIONS 7

A. Recommended Research

V. AEROBIOLOGY 8

A. Recommended Research

VI. CONCLUSION 10

APPENDIX A 13

REFERENCES 14

I. INTRODUCTION

The microbiological aspects of diving cannot be considered in isolation; many of the problems discussed by other committees of the National Plan have a direct bearing on the relationships among divers, microbes, and environment. The man-microbe-environment relationship is both subtle and complex; a change in any one of the elements may have substantial effects on the others. For example, an increase in a diver's steroid level, caused either by stress or the administration of a drug, may sufficiently alter the host-organism relationship to allow a microorganism to cause an infection. Figure 13-1 depicts the interrelationship of the microbiological aspects of diving. Though this diagram concentrates on the man-microbe relationship, it also includes the cellular effects of pressure, temperature, humidity, and various gases. This is particularly important in the discussion of nutrient transport, cell envelopes, electron transport, cytoplasmic enzyme processes, inorganic metabolism, genomes, and cellular resistance.

Throughout this report, the committee has confined its attention to events, research, and recommendations which are applicable to operational diving; we have therefore only considered conditions within the 1-150 ATA range, and gases which are presently in use either in commercial or experimental diving. Much of the research reviewed by this committee was conducted under normal environmental conditions, i.e., one atmosphere and air, but there is ample evidence that increased pressures or altered gas mixtures elicit important changes in physiological activity at the cellular level (7,29,32). Though it is clear that increased pressures and alterations in the breathing gas have significant effects on the man-microbe relationship, research is urgently needed to define the consequences of these variables for diving.

II. MICROBIAL PHYSIOLOGY

The study of infectious diseases in hyperbaric medicine comprises three broad areas of research: the effects of hyperbaria on the host, on the infectious disease agents, and on the host's response to the infectious agent under hyperbaric conditions. The complex nature of the host-parasite relationship in any circumstance makes the study of this relationship particularly difficult under hyperbaric conditions. Complicating factors which occur in hyperbaric chambers include increased pressure, altered breathing gases, and variations in temperature and relative humidity. Because hyperbaric experiments are inherently complex, most microbiological studies must be refined, well-planned, and basic experiments.

This section is concerned with research which will elucidate the effects of the hyperbaric environment on non-viral infectious disease agents. Many workers have reported that such effects occur in microorganisms at a basic level. Hyperbaric oxygen, for

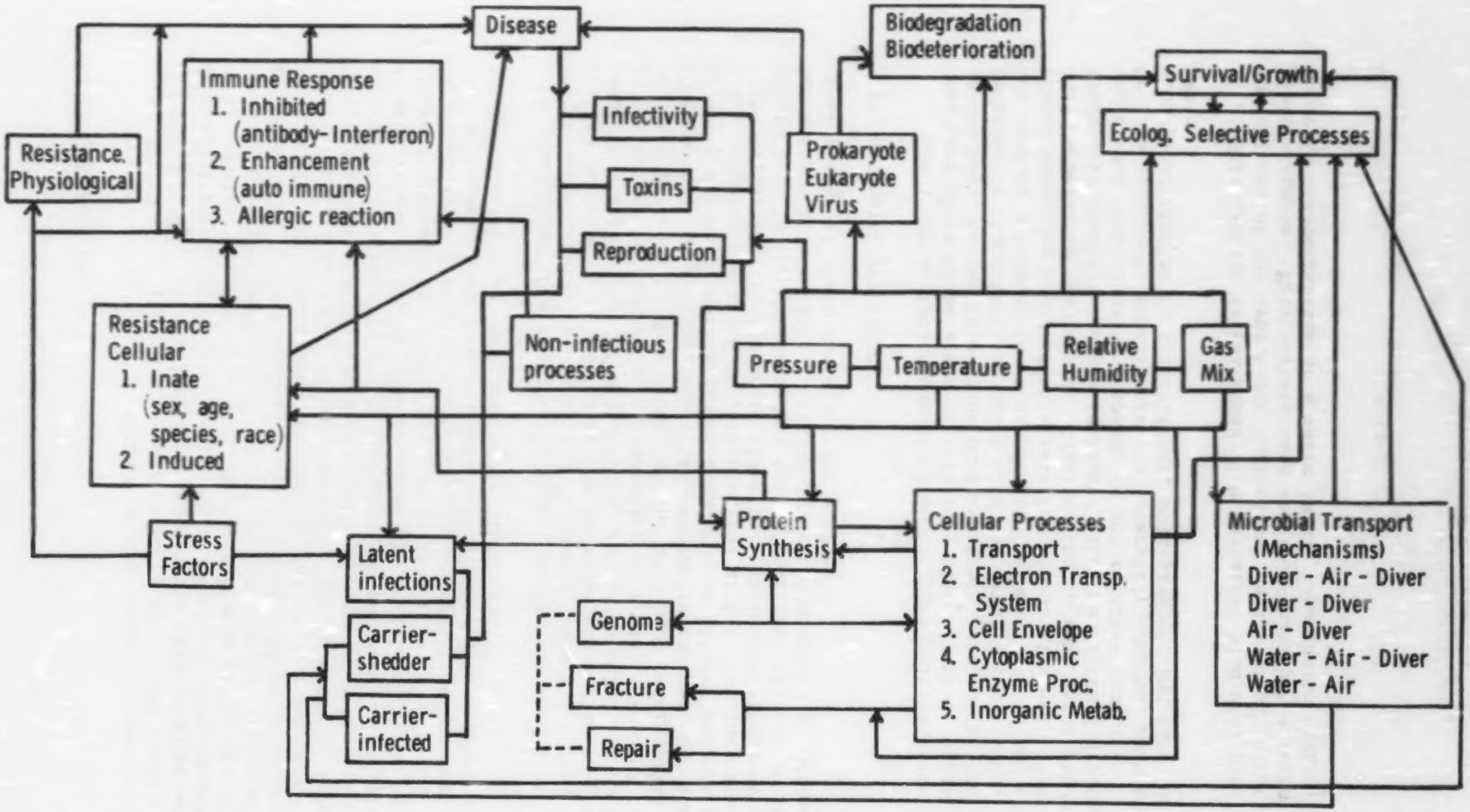


Fig. 13-1. Interrelationship of human, microbial, and environmental conditions and processes. Though the schematic representation of protein synthesis properly belongs with cytoplasmic enzyme processes, it is isolated here to emphasize its specific and varied interactions with other processes. The diagram is designed to show the effects of diving conditions, such as relative humidity, various gases, temperature, and pressure, on the man-microbe-environment relationship.

example, caused an increase in the production of superoxide dismutase in the bacteria Escherichia coli (11), while Hill and Osterhout (13) reported decreased pathogenicity in several anaerobic bacteria after exposure to hyperbaric oxygen. Schlamm and Daily (31) reported increased rates of carbohydrate transport in Escherichia coli at 68 ATA of normoxic helium, and Schlamm, Perry, and Wild (30) reported increased iron transport in the same organism, and increased alanine transpeptidase activity in Staphylococcus aureus under similar environmental conditions. These reports are drawn from previous studies and studies in progress, but much of the work is preliminary in nature and requires both confirmation and expansion.

A. Recommended Research

Research is needed on the effects of hyperbaric conditions on the permeability of chemicals in microbial processes, microbial metabolism of organic and inorganic compounds, enzyme activity, and protein synthesis. These effects may, in turn, influence related systems, e.g., DNA and RNA synthesis in microorganisms, which should also be investigated.

If hyperbaric conditions affect protein synthesis, the implications for the disease process would be profound; alterations in clinically significant characteristics such as infectivity, pathogenicity, growth rate, endo- or exotoxic production, and resistance to antibiotics or other toxic materials might be involved. A study of these factors is therefore also important.

Several published reports suggest that hyperbaric conditions have a fundamental effect on the physiological properties of tissue culture cells as well as microbial cells. Examples of effects observed include alterations in permeability and incorporation of amino acids and RNA precursors. Because of the implications of these findings for the health of divers, comprehensive studies with cell cultures should be conducted.

It is probable that hyperbaric conditions affect physiological systems involving DNA; studies investigating this possibility and emphasizing mutation rates, transformation rates, recombination, genome expression, and dissociation rates, should be planned. In preliminary and unpublished experiments, Wild adapted a widely accepted microbial system designed to detect carcinogenicity in industrial pollutants to a determination of potential carcinogens among the atmospheric contaminants which frequently occur in manned pressure chambers. Studies on the genetic effects of hyperbaria and on the carcinogenicity of toxicants are of great importance and should be conducted soon.

There is at present no information on the effects of hyperbaria, under normal PO_2 conditions, on the physiology of anaerobic bacteria, which are extremely important in the host-parasite relationship. These should therefore be investigated as part of any hyperbaric microbiology program.

Recent *in vitro* findings showed that the susceptibility of several bacterial species to certain antibiotics was altered under hyperbaric oxygen or normoxic helium conditions. This effect was also partially attributed to changes in enzyme production or activity. Such *in vitro* studies should be expanded to include a broader range of microorganisms and antibiotics. *In vivo* animal studies which parallel these *in vitro* studies have recently been undertaken. This research is preliminary, and of necessity laborious and time-consuming, but it should be continued and expanded because of its great medical importance.

There is a substantial amount of information in the literature on the susceptibility of animals to disease agents in hyperbaric chambers. However, the mechanisms involved have not been determined. Because of the recent and rapid increase in the understanding of immune systems, it would now be advantageous to continue such experiments and to consider the results in terms of hyperbaric effects on the immune response.

The following is a summary of needed research in order of priority.

1. Hyperbaric effects on susceptibility of the host to infectious disease agents

2. Hyperbaric effects on the host's immune response

3. Hyperbaric effects on the efficacy of chemotherapy in combatting infections

4. Hyperbaric effects on infectivity, pathogenicity, and growth rates of disease agents

5. Hyperbaric effects on medically relevant properties of anaerobic disease agents

6. Hyperbaric effects on the susceptibility of the host to bacterial toxins

7. Hyperbaric effects on bacterial mutation, transformation, and dissociation rates

8. Hyperbaric effects on physiological systems of microbial or mammalian cells, such as permeability, enzyme activity, synthesis of proteins, DNA, RNA, metabolism, requirements for growth factors, or limiting nutrients

9. Potentially carcinogenic airborne toxicants in hyperbaric chambers, using a microbial detection system

Hyperbaric effects on the fundamental properties of infectious disease agents indicate a need for research in other broad areas, e.g., changes in the immunity or disruption of the normal floral balance of the host. The microbial cell can also be used as a model for the cell in tissues or intact organs, and alterations in metabolism or synthetic processes in the microorganisms would therefore suggest similar physiological alterations in the tissues or organs of hyperbaric personnel.

III. HYPERBARIC OXYGEN AND VIRUS INFECTION

A. Enhanced Virus

Interaction between the mammalian host cell and infective viruses under hyperbaric oxygen conditions has been demonstrated repeatedly in both cell culture and whole animal systems (22,28,33). The advantages and results of both systems will be reviewed, and their future use considered.

Cell culture systems permit direct visualization of virus-induced cell pathology, which in turn allows qualitative and quantitative evaluation of the consequences of virus replication under normal and hyperbaric oxygen conditions. In addition, the mammalian cell culture system (human or other), with its relative degree of genetic uniformity, provides many similar test substrates for simultaneous testing of many variables. The absence of humoral antibody mechanisms associated with the intact animal is another simplifying factor in analyzing cell culture infections.

Enhancement of viral infection by hyperbaric oxygen has usually been demonstrated in cell cultures by an acceleration of virus maturation, production of abnormally higher yields, or faster cell destruction (1,24). The effects of hyperbaric conditions do not depend on continual exposure during the infectious cycle, and do not seem to act on the inoculated virus, attachment, or early stages of virus replication.

The evidence, though sparse, suggests that the effect of hyperbaric oxygen is expressed via changes in the membrane of the cell and lysosomes. Cell membrane changes would partially explain the observed increased rate of cell detachment and loss of viability of cell monolayers (23).

Increased lysosome membrane stability in infected cell monolayers exposed to hyperbaric oxygen was seen with acridine orange fluorescence staining (23). Stabilized lysosome membranes reduce the leakage of RNase, which in turn lessens the opportunity for viral RNA degradation and favors virus replication (16).

Animal systems have been used to study changes in mortality, virus content of target tissues, antibody profiles, and interferon production. In those cases where hyperbaric oxygen has enhanced infection, increased mortality has been accompanied by higher virus content in tissue (22).

There is evidence that hyperbaric oxygen acts by at least two pathways in animal systems. More viruses and less leakage of lysosome enzymes (RNAse, Beta-glucuronidase) are found in the hearts of mice exposed to 100% oxygen at 3 ATA for 15 minutes prior to being infected with Coxsackie virus, than in comparable mice kept in normal conditions. Animal experiments have also confirmed that hyperbaric oxygen inhibits the interferon activity found initially with cell cultures. Mice infected with Coxsackie virus after exposure to hyperbaric oxygen showed significantly lower heart tissue interferon levels; this effect could be prevented by adrenalectomy (21). Further evidence that hyperbaric oxygen acts, at least in part, via the adrenals was obtained by inoculating mice with adrenochrome and Coxsackie virus under normal conditions. These mice exhibited enhanced mortality, decreased enzyme leakage, and increased virus yield, just as if they were exposed to hyperbaric oxygen (26). In another experiment, inoculation of adrenalectomized and infected mice exposed to hyperbaric oxygen with adrenochrome nullified the inhibitive effect on interferon production which adrenalectomy usually causes (26).

Results implicating the adrenals in the viral enhancement which occurs in hyperbaric oxygen conditions are not surprising, in view of the well-known role of the adrenals in the oxygen toxicity syndrome of animals (19,14,36).

The fact that adrenochrome binds to ribosomes and inhibits polypeptide synthesis is compatible with the evidence that hyperbaric oxygen stress leads to selective inhibition of cell protein synthesis, resulting in lowered interferon production, and the depression of cell protein synthesis usually associated with the early stages of virus replication (34).

Although some contradictory results have been obtained, both in cell culture and animal systems (8,27,39), investigations of the role of hyperbaric oxygen in virus infection should be continued and expanded for several reasons. First, the nature of virology is changing radically. In the past, it has been possible to understand many of the clearly cytopathic viral-cell interactions by means of the conventional model: (a) the normal state (b) introduction of a virus (c) overt changes in the host (d) relatively quick "recovery" or "death", usually accompanied by a well-defined humoral response. Recently, several groups of viruses which differ in chemical and physical properties but have a common pattern of latency or chronic infectivity have received much attention. These are the "slow viruses" and those implicated in neoplasia etiology, such as the Oncorna and Herpes virus group (3,35,40).

If it is true that many, if not all of us, are infected early and throughout our lives with viral genomes which are not expressed until "triggered", it is imperative that every possible trigger mechanism be investigated, particularly in potentially high-risk populations, e.g., diving and support personnel who are repeatedly exposed to hyperbaric oxygen. Strong evidence that hyperbaric oxygen exacerbates the growth of slow viruses was obtained in experiments demonstrating that visna virus replication was enhanced under hyperbaric oxygen conditions (25).

In summary, hyperbaric oxygen appears to enhance some virus infections, both in cell cultures and animal systems, presumably by favoring virus formation and simultaneously impeding, at least partially, the host's defenses.

B. Recommended Research

To clarify the possible hazards to humans of hyperbaric oxygen, *in vivo* and *in vitro* investigations are needed. Hyperbaric oxygen appears to play a dual role in virus infections: in some cases, it activates a latent infection (either short-term or chronic), which would otherwise remain quiescent; in other situations, it heightens an individual's susceptibility and exaggerates the sequelae of illness.

1. Cell Culture Studies

The following research is suggested:

A systematic screening of selected representatives of the major groups of animal viruses, using both standard and modified procedures for virus isolation in standardized cell culture systems. Such a study ought to disclose patterns of virus properties and responses to hyperbaric oxygen conditions.

A combined electron microscope (both transmission and scanning) and chemical composition (e.g., role of surface glycoproteins or cyclic AMP, cell antigen receptor sites) study to elucidate the role of membrane integrity and its modification by viral response. The objective would be to determine the effects of hyperbaric oxygen and viral infection on structural and functional changes in the trilaminar membrane of the host cell and its organelles.

Changes induced by hyeprbaric oxygen which occur during the early stages of viral replication in cell culture systems should be studied. Such studies would help to elucidate the mechanism by which hyperbaric oxygen exerts its effect at the cellular level.

2. Animal Experimentation

Very little information on humoral and cell-associated antibody profiles with hyperbaric oxygen and virus infection is available. Research using species with different patterns of antibody response to the same viral antigen would shed light on the immune response associated with hyperbaric oxygen. These same animal experiments could also increase our understanding of the synthesis of interferon and its modification under experimental and hyperbaric field conditions. A clearer understanding of the related but distinct roles of associated antigen in virus replication and immunization under hyperbaric conditions would increase our knowledge of the use of antioxidants and other protective drugs.

3. Human Studies

There are few short-term, and fewer long-term, studies on the isolation of viruses and viral antibody profile analyses of humans using the varying exposures found in diving (4,8). Several kinds of research should be conducted in this field.

a) Standard epidemiologic procedures using ordinary cell culture virus isolation and serologic procedures. The advantage of these techniques is that a large number of samples could be processed; the disadvantage is the possibility that latent and chronic infections would not be apparent.

b) Other methods such as electron microscope and immunologic assays of leukocyte cultures or biopsy specimens from divers might be useful. Tissue from human cadavers which is subjected to hyperbaric conditions would provide model systems closely approximating the living subject.

IV. IMMUNOLOGIC CONSIDERATIONS

Whenever a group of persons or animals live together in close proximity for several days or weeks, they undergo an initial period of illness; after recovery from these initial infections, they are immune to subsequent infections from endogenous agents as long as they live in isolation with their antigenic peers. However, they are extremely susceptible to infection from exogenous agents whenever the isolation period ends and contacts are re-established with "outside" personnel and family members. Such "herd-infection, herd-immunity" findings have been noted in respiratory problems found in Polaris submarine crewmembers, persons living in Antarctica, and mouse populations (2,10,17,18,19,37,38). Workdays lost because of this phenomenon have not been recorded and the cost of decreased efficiency and discomfort are almost impossible to calculate.

Government or industry, however, could incur a life-long liability if a young person was permanently incapacitated by a disease such as tuberculosis as a result of close confinement in a contaminated undersea habitat.

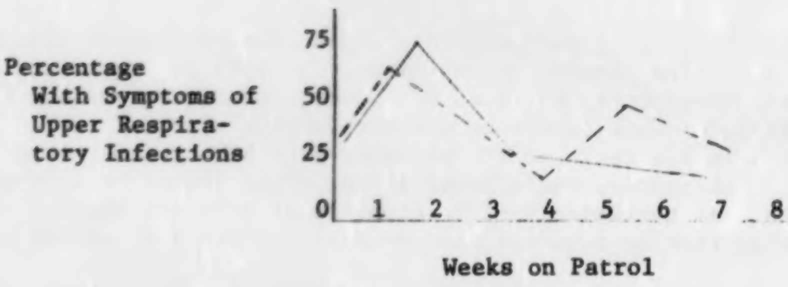


Fig. 13-2. Graph of two Polaris patrols; solid line = unbroken isolation for duration of patrol; broken line = discontinuous isolation (three crew members made exogenous contacts during Week 4 of patrol, which resulted in recurrence of respiratory symptoms)

A. Recommended Research

This visual presentation of the herd-infection, herd-immunity phenomenon in humans demonstrates the potential for tragedy if an illness more serious than a cold is involved. The following research should clarify, and perhaps point to methods to modify and control, this phenomenon:

1) Determination of safe pre- and post-isolation periods

2) Determination of types of immunization effective against this phenomenon

3) Determination of methods for enhancement of viral interferon production, as affected by pressure, temperature, relative humidity, and gas mix

4) Effects of pressure, temperature, relative humidity, and gas mix on slow-acting viruses

5) Effects of pressure, temperature, relative humidity, gas mix, body heat loss, and fatigue on the triggering mechanisms of subclinical and latent infections

V. AEROBIOLOGY

This section will deal with the effects of pressure, temperature, gas mix, and relative humidity on the survival, selectivity, and transport mechanisms of microorganisms.

Earlier work in aerobiology has shown that humans disseminate airborne particulates of varied concentration, size, and composition. Some of these particulates containing microbes are small enough (1-2 micron) to journey readily to the alveoli of the lungs and to be retained for long periods (20). Such aerosols derived from humans may be infective, toxic, or antigenic, not only for the diver and his immediate co-workers, but also for subsequent divers working from the same habitat. This is due to the persistence of these small particles in the recycled air of underwater habitats for long periods. Therefore, operational diving sites should be assayed for microbial air contamination; maintenance of good air hygiene within the diving habitat requires that biohazard control be effective.

The mechanisms of disease transmission by the airborne route within the habitat need to be determined, as well as the factors which contribute to the survival, death, and transmission of microbes. The effects of pressure, temperature, relative humidity, various gases, and different diving modes on microbes, the health of divers, and the contamination of habitats need to be evaluated.

The TEKTITE I program demonstrated that marine bacteria can be transported mechanically from the marine environment, and can assume a predominant role in the air flora of the habitat (5), and the skin of the diver (6). Hatch and Dimmick (12) have shown that the relative humidity most detrimental to those airborne bacteria studied at 1 ATA was in the area of 50%, i.e., bacteria are least able to survive at a relative humidity of 50%. Though the TEKTITE habitat was maintained at 50%, ± 5%, the predominance of a marine organism occurred.

During TEKTITE I, Pseudomonas aeruginosa was found in the air of the habitat just before two divers developed debilitating ear infections caused by this organism. Just before this pathogenic bacteria was found in the air of the habitat, another diver developed an ear infection which was also caused by this organism. It could not be determined whether these events were dependent or independent.

It was also noted during this study that the yeast Rhodotorula, initially found only in one diver, had become common to all divers by the end of the mission (15). This was also noted in nasal carriers of Staphylococcus aureus (unpublished observations).

The number of varieties of bacteria in the air flora of the habitat decreased during the TEKTITE mission, though the total number of bacteria increased, a process known as simplification. This has also been noted in numerous NASA reports dealing with closed environments. The explanation and mechanisms of simplification and the characteristics of an organism which allow it to be selected and/or survive for extended periods are at present unknown.

A. Recommended Research

It was fortunate that the marine bacteria in the TEKTITE program were not pathogenic, or grave consequences might have resulted. There are a number of unanswered questions about microorganisms in the hyperbaric environment. How did Pseudomonas aeruginosa become part of the air flora of the habitat, and once there, why didn't it remain and ultimately predominate? Are marine bacteria affected by a relative humidity of 50%, as are those terrestrial types that have been studied, and does the pressure-gas mix play a role in this effect of relative humidity? This question also relates to the air transmission of potentially pathogenic organisms by nasal carriers of Staphylococcus aureus and Neisseria meningitidis, and the ultimate survival of the organisms in the air flora. The following research is proposed to address these questions.

1. Determine the effect of different pressures, temperatures, and gas mixes on the survival of airborne microbes at different relative humidities.

2. Determine the optimal method of decontaminating the interior atmosphere and/or surfaces of a habitat.

3. Determine the characteristics of bacteria or fungi which allow them to become the predominant organism through selective pressure.

4. Determine the role that the physical transport of an organism plays in its ultimate survival and selectivity.

5. Determine the carrier's role in the selectivity and/or survival of airborne organisms.

6. Determine the role of pressure, temperature, relative humidity, and gas mix on selective pressure and the survival of the organism.

When the extent of such hazards are assessed, protective measures which will decrease the amount of circulating airborne contaminants, both by modifying human physiology and by treating the circulating environmental air, should be found.

VI. CONCLUSION

This report has been divided into several sections; priorities have been determined for each section, but overall priorities have not been established.

Because the scope of our topic was so broad, the committee chose not to name specific laboratories to perform the recommended research. Laboratories working on the microbiological aspects of diving should in general meet the following qualifications:

1) Microbiologists (bacteriologists, virologists, mycologists, and so forth) with background experience and publications in the field of hyperbaric microbiology;

2) A staff bioengineer experienced in experimental hyperbaric chamber work;

3) Shop facilities staffed by personnel experienced with hyperbaric equipment;

4) Hyperbaric pressure equipment appropriate to the research program involved.

As is usual under other circumstances, all research proposals should be evaluated on the basis of these qualifications. Experimentation in hyperbaric microbiology is exceptionally complex and time-consuming, and generally requires a relatively large technical laboratory staff. In view of the high costs involved in establishing temporary field laboratories, we also recommend that samples collected during manned diving chamber operations in remote areas be transported to permanent laboratories for processing.

APPENDIX A

ORAL HEALTH AND DENTAL INFECTIONS IN DIVING

Capt. M. Mazzarella, DC, USN

Minor oral health problems which are not detected at ambient pressure and atmosphere often develop into painful and dangerous infections under hyperbaric conditions. For example, a partially erupted wisdom tooth in a completely quiescent state became infected and painful and threatened to incapaciate a diver during the OPS I project. Local and systemic treatment was initiated, and the diver was able to continue. However, the drug did not work as rapidly as would be expected under conditions of ambient pressure and atmosphere. In another observation, simultaneous multiple eruptions of herpetic lesions caused extreme discomfort for one diver during the course of a short dive at New London. Similar, less-acute episodes of oral aphthae, anatomical deformations of palatal tissue, and vascular engorgements of pharyngeal tissues have been noted on occasion in other diving personnel.

Oral health research should be divided into three major areas: 1) Operational, 2) Epidemiological, and 3) Pathophysiological.

Operational research would concentrate on the prevention of oral health problems which could rapidly become acute under diving conditions, causing the dive to be aborted.

Epidemiological research would deal with the prevalence, etiology, and pathology of overt dental disease, such as caries and periodontitis, which contribute to inefficiency due to lost man hours.

Pathophysiological research would be concerned with subtle and transitory or insidious oral health changes caused by the hyperbaric environment, which might lead to compensable disabilities. Such research should emphasize prevention of future oral disease, debilitation, and/or compensation.

Research on the operational and epidemiologic aspects of oral health is best undertaken using routine oral and radiographic examinations; intra-oral color photographs and gypsum casts of dentition should also be maintained as part of each diver's permanent record. Subtle changes are best monitored by using salivary microbial profiles obtained from periodic assays of paraffin-stimulated, physiologically inactive pooled-saliva collections, gathered during diving operations.

Such research should be designed to 1) eliminate predictable and acute dental emergencies; 2) establish oral health standards for diving personnel and increase mission efficiency; and 3) eliminate future liability claims, by noting subtle and insidious changes in the oral health of diving personnel.

REFERENCES

1. Baron, S., J. S. Porterfield, and A. Isaacs. 1961. The influence of oxygenation on virus growth. I. Effect on plague formation by different viruses. Virology 14:444-449.
2. Cameron, A. S., and B. W. Moore. 1968. The epidemiology of respiratory infection in an isolated Antarctic community. J. Hygiene 63:105-116.
3. Carter, W. A., and Erik DeClercq. 1974. Viral infection and host defense. Science 186:1172-1178.
4. Cobet, A. 1969. Final TEKTITE report. Oakland, California: Nav. Biomed. Res. Lab.
5. Cobet, A. B., and R. L. Dimmick. 1970. TEKTITE I program: aerobiological aspects. Aerospace Med. 41:617-620.
6. Cobet, A. B., D. N. Wright, and P. I. Warren. 1970. TEKTITE I program: bacteriological aspects. Aerospace Med. 41:611-617.
7. Daily, O. P., and N. A. Schlamm. 1972. Effect of hyperbaric atmospheres on beta-galactoside transport in Escherichia coli. Can. J. Microbiol. 18:1162-1164.
8. Danziger, R. E., T. L. Sallee, D. E. Liddin, E. T. Flynn, and J. M. Alexander. 1971. Case of mumps during hyperbaric exposure. Aerospace Med. 42:1335-1337.
9. Drysdale, D. B. 1971. The effects of adrenalectomy and adrenaline upon rats exposed to oxygen at high pressure. Proc. Univ. OTAGO Med. Sch. 49:7-8.
10. Greenwood, M., A. B. Hill, W. W. C. Topley, and J. Wilson. 1936. Experimental Epidemiology, Rept. 209. London: Medical Research Council.
11. Gregory, E. M., and I. Fridovich. 1973. Oxygen toxicity and the superoxide dismutase. J. Bacteriol. 114:1193-1197.
12. Hatch, M. T., and R. L. Dimmick. 1966. Physiological responses of airborne bacteria to shifts in relative humidity. Bacteriol. Rev. 30:597-602.
13. Hill, G. B., and S. Osterhout. 1974. In vitro and in vivo effects of hyperbaric oxygen on nonsporeforming anaerobic bacteria. In: Oxygen. Proc. 5th Intern. Hyperbaric Congress, edited by W. G. Trapp, E. W. Bannister, A. J. Davison, and P. A. Trapp. Burnaby, Canada: Simon Fraser Univ.
14. Houlihan, R. T., M. D. Altschule, Z. L. Hegedus, and M. H. Cross. 1970. Rheomelanin accumulation in the blood and lungs and hemolysis in rats poisoned by hyperbaric oxygen. Proc. 4th Intern. Congress Hyperbaric Med.
15. Levine, H. B., J. M. Cobb, and A. B. Cobet. 1970. The TEKTITE-I dive. Mycological aspects. Arch. Environ. Health 20:500-505.
16. Lwoff, A. 1969. Death and transfiguration of a problem. Am. Soc. Microbiol. 69th Annual Meeting.
17. MacLean, A. L. 1919. Bacteriological and other researches. Scientific Rept. Australia's Antarctic Expedition.

18. Mazzarella, M. A., H. M. S. Watkins, M. A. Chatigny, and H. Wolochow. 1966. Epidemiological studies aboard polaris submarines. Nav. Biol. Lab., 39th Tech. Prog. Rept.

19. Mazzarella, M. A., H. M. S. Watkins, C. E. Meyers, H. Wolochow, and M. A. Chatigny. 1963. Epidemiological investigations aboard polaris type submarines. Nav. Biol. Lab., 39th Tech. Prog. Rept.

20. Micik, R. E., R. L. Miller, M. A. Mazzarella, and G. Ryge. 1969. Aerobiology and dental procedures. J. Dental Res. 48:49-56.

21. Orsi, E. V., R. Markowski, and T. Russo. 1971. Coxsackievirus mortality and lysosome enzyme patterns altered by adrenochrome and hyperbaric oxygen. Bacteriol. Proc. V60.

22. Orsi, E. V., R. Mancini, and J. Barriso. 1970. Hyperbaric enhancement of coxsackievirus infection in mice. Aerospace Med. 41:1169-1172.

23. Orsi, E. V., F. Minivaggio, and B. Vassallo. 1970. Hyperbaric enhancement of coxsackievirus pathogenesis of human cell cultures. Bacteriol. Proc. V64.

24. Orsi, E. V., J. Barriso, and R. Mancini. 1969. Hyperbaric oxygen enhancement of coxsackievirus B_1 infection in human cell cultures (HEp-2) and young mice. Bacteriol. Proc. V93.

25. Orsi, E. V., and N. Z. Baturay. 1975. Hyperbaric oxygen enhancement of VISNA infection of cell cultures inhibited by metabolic stimulants (Abstracts). Amer. Soc. Microbiol. Rept. 22.

26. Orsi, E. V., A. Kuenzel, M. Bahrt, A. Pajares, and J. Napoli. 1972. Interferon levels following hyperbaric oxygen stress in adrenalectomized mice. Bacteriol. Proc. V75.

27. Panov, A., and G. Remezov. 1960. Effect of oxygen under pressure on the course of certain experimental neurotropic virus infection in white mice. Problems Virol. 5:290-296.

28. Sawicki, L., S. Baron, and A. Isaacs. 1961. Influence of increased oxygenation on influenza virus. Lancet 680.

29. Schlamm, N. A. 1972. Effect of elevated atmospheric pressure on antibiotic susceptibility of Staphyloccus and Streptococcus pyogens. Antimicrobiol. Agents Chemotherapy. 1:512-513.

30. Schlamm, N. A., J. E. Perry, and J. R. Wild. 1974. Effect of helium gas at elevated pressure on iron transport and growth of Escherichia coli. J. Bacteriol. 117:170-174.

31. Schlamm, N. A., and O. P. Daily. 1972. Effect of hyperbaric atmospheres on beta-galactoside transport in Escherichia coli. Can. J. Microbiol. 18:1162-1164.

32. Schlamm, N. A., and J. E. Perry. 1970. Growth of Escherichia coli in high pressure helium-oxygen atmospheres. U.S. Nav. Med. Res. Inst. Rept. 1.

33. Segre, D. 1964. Cytopathic effects of normally non-cytopathogenic viruses in tissue cultures held under increased oxygen pressure. Proc. Soc. Exp. Biol. Med. 117:567-569.

34. Shafritz, D., F. Goodwin, and H. Weissbach. 1969. Inhibition by aminochromes of in vitro polypeptide synthesis in Escherichia coli. Arch. Biochem. Biophysiol. 134:478-485.

35. Thormar, H. 1966. Physical, chemical and biological properties of visna virus and its relationship to other animal viruses. NINBD Monograph No. 2.

36. Taylor, D. W. 1958. Effects of adrenalectomy on oxygen poisoning in the rat. J. Physiol. 140:23-36.

37. Watkins, H. M. S., M. A. Mazzarella, C. E. Meyers, J. P. Hresko, H. Wolochow, M. A. Chatigny, and F. M. Morgan. 1964. Respiratory infection and microbial burden of the atmosphere within a nuclear submarine. Nav. Biol. Lab., 36th Tech. Prog. Rept.

38. Webster, L. T. 1933. In: Principles of Bacteriology and Immunity, edited by G. S. Wilson and A. A. Miles. 1955. Baltimore: Williams and Wilkins Co.

39. Zajac, I., and L. M. Pakman. 1974. The effect of high pressure oxygen on in vitro and in vivo infections with CVI Vaccinia virus. In Vitro: 9:365.

40. Zeman, G. B., and E. H. Lennette. 1974. Slow Virus and Diseases. Baltimore: Williams and Wilkins Co.

THERMAL PROBLEMS

Part #14 of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Paul Webb, M.D. (Chairman)
Principal Associate
Webb Associates,
Yellow Springs, Ohio

Wallace T. Jenkins
Research Oceanographer
U.S. Naval Coastal Systems Laboratory
Panama City, Florida

Charles E. Johnson
Dept. of Mechanical Engineering and Material Science
and F. G. Hall Laboratory for Engineering Research
Duke University
Durham, North Carolina

Richard W. Long
President, Diving Unlimited International
San Diego, California

Lawrence W. Raymond, CDR, MC, USN
Head, Pulmonary Branch
National Naval Medical Center
Bethesda, Maryland 20014

N. Eugene Smith
Engineering Manager
Sub Sea International
New Orleans, Louisiana

TABLE OF CONTENTS and Organization for part 14

Thermal Problems

I. INTRODUCTION 1

II. INTERIM GUIDELINES FOR HUMAN THERMAL TOLERANCE 2

III. HEAT EXCHANGE IN DIVERS 2

IV. THERMAL MONITORING 3

V. INSULATING MATERIALS 4

VI. REWARMING 4

VII. POWER SOURCES 5

VIII. GAS PROPERTIES 5

IX. IMPROVED CO_2 ABSORBENTS 6

X. PERFORMANCE, BODY TEMPERATURE, AND BODY HEAT LOSS 6

XI. EVAPORATIVE HEAT TRANSFER 6

XII. PRIORITY LIST OF RESEARCH NEEDS 6

XIII. RESEARCH FACILITIES 7

XIV. CONCLUSION 10

I. INTRODUCTION

In 1973, the JOHNSON-SEA LINK submersible became entangled in debris in 350 feet of water off Key West. Plans called for the dive to last only a few hours; before the submersible could be recovered, several days had passed. As the temperature inside the vehicle approached the water temperature of 6°C (43°F), the men inside became chilled and the CO_2 scrubber became less efficient. Two of the divers died, either directly from the cold or from CO_2 poisoning, which may have been an indirect effect of the cold. Four years earlier, the mobile habitat Aegir was submerged to 506 fsw in a saturation dive in the warm waters off Hawaii. The oxygen-helium environment was maintained at 25°C (77°F); the men inside the habitat shivered and complained of cold throughout the dive. Even more disappointing, the divers could not stay in the water because of the intense cold. The men were unable to cooperate in solving some serious operational problems. Rewarming was ineffective inside the habitat. The medical office described the dive as an unintentional study of prolonged cold exposure.

The Navy's SEA LAB project was hampered and finally halted by what now appear to have been thermal problems. SEA LAB II (1965) was a saturation dive to 205 fsw in 9°C (48°F) water. It took a coordinated effort by a team of well motivated men to overcome the soaking cold the men experienced every time they entered the water. Their wet suits were compressed and ineffective, and it seems probable that breathing unheated helium added to the cold exposure. Operational time outside the habitat was only a fraction of what could reasonably be expected of thermally comfortable divers. Despite the time, money, and energy put into SEA LAB II, each man spent an average of less than one hour each day in the water.

SEA LAB III (1969) was the next stage in this program. The original SEA LAB II vessel was modified and placed at a depth of 620 fsw in 7°C (45°F) water. Before the habitat could be occupied, a number of problems developed, including serious helium leaks. Inspections were made by diving teams operating from an unheated and uninsulated personnel transfer capsule (PTC) which caused serious cold exposure. On the first of two dives, one of the divers returned to the PTC prematurely; he was so thermally stressed that he was unable to talk to his tenders inside. Several hours later the same man died during the second dive. Many feel that the severe cold exposure associated with both diving attempts was a major contributing factor in this fatality.

Though these three experiments may seem like ancient history, there was a double fatality on an oil rig this fall (1975). A preliminary account by the investigating physician who visited the scene indicates that the two divers probably died of heat stroke in the deck decompression chamber. The divers had been working from a submerged bell and had returned to the surface for decompression. They transferred from the bell to a preheated decompression chamber whose temperature was said to be between 110-120°F. Shortly after they reached the DDC, the chamber pressure was raised to 21 ATA (650 fsw) which probably raised the temperature even higher; then the pressure was lowered to 13 ATA. The duration of the entire exposure is still uncertain, but the men were probably exposed for 20, and perhaps for as long as 40 or 50 minutes. Observers noted that the divers inside were agitated and appeared to have headaches, which are prodromal signs of heatstroke. The men then lost consciousness, and were dead before they could be removed from the chamber. It seems highly likely that heatstroke was the cause of death. Such an event is a dramatic reminder of the extreme heat-transfer capacity of hyperbaric gas, for had the conditions been air at one atmosphere, the heat exposure would have been mild and the duration short.

Diving is a cold activity; cold is both limiting and lethal. The traditional "tough diver" cannot operate with traditional diving gear at the depths and with the gases now being used. In recent years, for example, it has become clear that respiratory gases must be heated in cold water at depths of 600 fsw.

It is generally believed that cold is the type of environmental stress which could readily be eliminated by a sufficient engineering effort. Some observers point out that cold exposure could be eliminated by sending unmanned vehicles and manipulators to do the job. Making such solutions operational will take time and extravagant amounts of money, and even then many underwater jobs will still require divers. The committee has identified a number of problems, ranging from heat transfer in hyperbaric gas to the physiology of comfort and thermal tolerance limits in hyperbaric chambers, which need research. This report discusses ten major topics which are of primary importance in removing the limits imposed on diving by current thermal problems. These topics are: 1) Interim guidelines for human thermal tolerance; 2) Heat exchange in divers; 3) Thermal monitoring; 4) Insulating materials; 5) Rewarming; 6) Self-contained power sources; 7) Gas properties; 8) Improved CO_2 absorbents; 9) Performance, body temperature, and heat loss; and 10) Evaporative heat loss.

II. INTERIM GUIDELINES FOR HUMAN THERMAL TOLERANCE

Operational diving is now being done without sufficient information about thermal problems. Existing literature and other data should be analyzed to suggest interim guidelines for human thermal tolerance in hyperbaric conditions.

III. HEAT EXCHANGE IN DIVERS

A serious study of skin and respiratory heat exchange in divers is needed. Results from such a study would be useful operationally and in the design of thermal protective equipment. The lack of precise information makes it difficult to set thermal limits for depth or duration of exposure, either in the water or in dry habitats. A thermal comfort zone for diving gear or habitats can be approximately defined at present, but there is little experimental data to guide us in setting thermal limits for hyperbaric exposures below or above the comfort zone. It is clear that heat exchange is enormously accelerated, in either a water or hyperbaric gas environment.

An essential task is to re-explore the range of tolerable deviation from normal skin and body temperature under hyperbaric conditions. Human responses to new hyperbaric conditions must also be investigated. Occasionally, the results are surprising. For example, breathing cold dense hyperbaric gas causes a copious and disabling secretion of mucus, and such a rapid rate of heat loss from the body core that subjects shiver violently even while working hard in a warm environment.

The analytical approach to the problem is to devise predictive equations based on accurate heat transfer data, so that heat loss and body temperature can be predicted for any environment. A well organized and comprehensive experimental program to develop and test such predictive equations is needed.

Thermal problems in diving are only beginning to be explored. Most cold water research was stimulated by concern over accidental wartime immersion, which produced hypothermia and death. Most dives in the hyperbaric environment are done under comfort conditions; thermal exchanges are explored only as a secondary or minor objective. In actual diving, the diver faces thermal discomfort, often to a dangerous degree. We need careful experimental observations on tolerance to temperatures both above and below the comfort zone, and at the pressures anticipated in future commercial diving, perhaps up to 67 ATA (2,000 fsw).

IV. THERMAL MONITORING

Neither the diver, his tender, or his companion can properly judge the diver's thermal state. The onset of serious hypothermia is insidious, somewhat similar to the onset of oxygen deprivation; we suspect that the diver's performance is decreasing long before serious hypothermia develops. Similarly, as recent events have shown, we are not accustomed to looking for signs of hyperthermia; unconsciousness and death from this cause may come with unexpected swiftness. A reliable means of monitoring the diver's thermal state is urgently needed.

Thermal state monitors must not only be medically and physiologically accurate; they must also be acceptable to the diver and practical. The problem is not easy, either from the physiological or engineering standpoint. For example, it might be best to record core temperature by means of a radio pill which the diver had swallowed, but that would mean that the pill would have to be inexpensive, in case it cannot be recovered. Other possible but still untested techniques are: monitoring respiratory gas temperature, which is related to core temperature during exhalation, and which would also provide information about inspired gas temperature when the dive is deep; measuring the rate of blood flow in hands and feet or the rate of heat loss in discrete areas; and continuously monitoring the temperature of the diver's hand, which would be helpful in determing the diver's ability to work. A good thermal monitor would also be useful during rewarming.

V. INSULATING MATERIALS

Designers of protective diving equipment need better insulating materials for today's diving conditions. The only available noncompressible materials are not yet soft or pliable enough to make proper clothing. The relatively high thermal conductivity of present materials means that suits have to be too thick to be practical. Another problem is that some materials exchange gas with the hyperbaric environment, which changes their insulating properties. Other important and desirable characteristics of suitable insulation material include resistance to abrasion, puncture, and oil. Better insulation is also required for hoses and even the insulation in the relatively fixed configurations of bells and habitats could be improved.

The importance of such materials is obvious. If it were possible to limit the rapid and serious loss of body heat, supplemental heating might often not be required, or the power required to supply it could be minimized. Progress in thermal protection depends on the development of new insulating materials.

VI. REWARMING

Once a cold diver comes out of the water he must be rewarmed. The methods commonly employed are inadequate: hot showers and coffee are not sufficient to do more than restore a sense of thermal comfort while the diver may in fact still be in thermal debt. The diving operator often does not realize that a man is insufficiently rewarmed until he makes another dive and becomes severely cold in an exceedingly short time. The essential questions in rewarming are how to judge when rewarming is complete, and what are the best methods for various situations. Methods to be explored include hot water baths, the hot water suit, breathing moist hot air or oxygen, exercise, and stimulants. More research on methodology is desirable.

Scant attention has been paid to determining when a diver has been sufficiently rewarmed to return to diving. Physiologically, restoration of the normal thermoregulatory processes signals that rewarming is complete. However, these physiological signs are so subtle and difficult to measure that only a laboratory can make such determinations. Monitoring equipment which can determine when rewarming is complete is as essential as monitoring equipment to determine the diver's thermal state while he is working.

VII. POWER SOURCES

Just as the development of self-contained underwater breathing apparatus freed the diver and led to a great expansion of diving activities, the development of a self-contained power source to provide supplemental heating would greatly benefit diving operations. Supplemental heat is presently supplied through an umbilical cord, either via hot water or through electric power cables. At deeper depths, the cable length and environmental conditions make this approach more and more difficult. It is not practical in many cases to carry the thermal or electric generators required to supply supplemental heat to the dive site. Once the power requirement has been established, the development of self-contained power sources is primarily an engineering matter. Past efforts in this area must be classed as preliminary. Many early designs proved to be unsuitable for the diver underwater. Self-contained power sources would be useful not only for the diver himself but also as primary or emergency power for bells, submersibles, and swimmer delivery vehicles.

VIII. GAS PROPERTIES

The thermodynamic and physical properties of the gas mixture strongly influence heat transfer between the diver and the hyperbaric gas environment. Numerical values for these properties are presently based almost entirely on the characteristics of single gases; it is assumed that these properties combine according to classical theory. This is accurate if the interactions between the gases of a given mixture do not deviate from the assumed intermolecular force model. But gas mixtures containing water vapor, a polar molecule, are not described, because the intermolecular force model has not been verified for helium and water vapor or for trimixes. To determine these critical gas properties for the kinds of mixtures used in diving, empirical data must be gathered.

To write the heat exchange equations referred to in section III above, it is necessary to be able to describe convective heat transfer mathematically, based on gas properties and all the other relevant factors, such as local gas velocity, shape of the body, and temperature gradients. When such equations have been validated by experiment, reliable predictions about many combinations of gas pressure, temperature, and mixtures can be made. Specific determinations of these gas properties will also be useful in designing gas heat exchangers and environmental control systems for hyperbaric chambers, and in determining fluid flow in breathing apparatus.

The important gas properties are considered to be: specific heat, thermal conductivity, density, viscosity, diffusivity, enthalpy, and entropy. These should be determined for the common gas mixtures in the range of pressures used in diving.

IX. IMPROVED CO_2 ABSORBENTS

CO_2 absorbents are critical parts of certain breathing apparatus and life support systems of divers, and the efficient operation of materials is at present seriously influenced by the operating temperature. The operating life of CO_2 absorbers in submersibles, bells, and backpacks is shortened in the cold. The capacity or useful life of a specific canister of CO_2 absorbent may be only one third of normal when the gas being processed is cold. This may be partially corrected by improved canister design, but the effect of temperature itself is ultimately the limiting factor.

We recommend that the manufacturers of the chemicals used in CO_2 absorbents try to develop absorbing materials which are less affected by temperature in the range which is normally encountered in diving.

X. PERFORMANCE, BODY TEMPERATURE AND BODY HEAT LOSS

Current research on body heat loss by direct calorimetry should succeed in relating the commonly measured body temperatures to the quantity of heat lost in cold water. The next and most important research step will be correlating body heat loss with performance change, especially in the early stages of hypothermia. Clinical hypothermia begins when rectal temperature drops to 35°C (95°F); a lesser degree of hypothermia is often encountered in diving. However, there are performance changes, and perhaps significant ones, when body temperature is dropping from the normal state to that of clinical hypothermia. Measurements of performance for this temperature range should include tests of dexterity, strength, and the higher mental functions.

XI. EVAPORATIVE HEAT TRANSFER

In hyperbaric gas, the physical conditions for the evaporation of water are poor; at the same time the diving environment is more often than not quite humid. Diffusion between gases is reduced under high pressure, and gas mixing and gas motion are retarded. The process of evaporation from human skin and the respiratory tract needs to be examined in hyperbaric conditions. Though this process may be relatively unimportant in cool environments, the evaporative pathway is normally a major defense against heating of the body in hot environments, and it may well be that this major pathway is unavailable to the diver in a hyperthermic hyperbaric environment.

XII. PRIORITY LIST OF RESEARCH NEEDS

The committee has given the following priorities to the areas of research in thermal problems. We need to:

1. Establish interim guidelines, based on current knowledge, for human thermal tolerance to hyperbaric exposure.

2. Determine the skin and respiratory heat exchange of divers to: a) define safe limits for core, skin, and inspired gas temperatures; b) develop and test predictive equations for heat transfer; c) set thermal limits (wet/dry, depth, and time)

3. Find better ways to monitor the diver's thermal state

4. Develop improved insulation

5. Develop methods and endpoints to rewarm the cold diver

6. Design self-contained power sources for divers, bells, and submersibles

7. Determine thermodynamic and physical properties of diving gases

8. Develop improved CO_2 absorbents for the operational temperature range

9. Define the relationship between body heat loss, temperature, and performance

10. Investigate the role of evaporative heat transfer in hyperbaric gas environments

XIII. RESEARCH FACILITIES

Problems associated with thermal protection for divers are under investigation by a wide variety of universities, institutions, agencies, and independent research specialists. The amount and areas of research vary so that any listing by level of effort or capability is impossible. The following list is included to show the wide range of research interest in this field. It is divided into Active, those facilities which are currently working in thermal protection, and Potential, those organizations which have done such work in the past or which could easily do related work. Neither list is intended to be inclusive, nor should either be accepted as doctrine.

Active Laboratories

1. Defense and Civil Institute of Environmental Medicine
   Downsview, Ontario, Canada
   Lt. Fred Cox

2. Diving Unlimited, Inc.
   San Diego, California
   Dick Long

3. F. G. Hall Environmental Laboratory
   Duke University Medical Center
   Durham, North Carolina
   Peter B. Bennett

4. General Electric
   Environmental Systems Research and Development Dept.
   Philadelphia, Pennsylvania
   Lowrey Lady

5. Laboratoire de Medecine
   Aerospatiale, Centre d'Essais en Vol
   Marseille, France
   Dr. Jean Timbal and Dr. Boutelier

6. Mancini and Mowrey, Inc.
   46 Van Dyke
   Thousand Oaks, California

7. Naval Civil Engineering Laboratory
   Port Hueneme, California

8. Naval Coastal Systems Laboratory
   Panama City, Florida

9. Naval Medical Research Institute
   National Naval Medical Center
   Bethesda, Maryland

10. Naval Submarine Medical Research Laboratory
    Groton, Connecticut
    Karl Schaefer

11. Oceanautics, Inc.
    Landover, Maryland
    William Vaughan, Jr.

12. S.U.N.Y. at Buffalo, New York
    Herman Rahn

13. U.S. Navy Experimental Diving Unit
    Panama City, Florida
    William Spaur

14. University of Calgary
    Calgary, Alberta, Canada
    Keith Cooper

15. University of Hawaii
    Honolulu, Hawaii
    T. O. Moore

16. University of Rochester
Rochester, New York
A. T. K. Cockett

17. Webb Associates
Yellow Springs, Ohio
Paul Webb

Potential Laboratories

1. Capt. Albert R. Behnke, MC, USN, Ret.
2241 Sacramento St.
San Francisco, California

2. Institute of Environmental Medicine
University of Pennsylvania
Philadelphia, Pennsylvania
C. J. Lambertsen

3. Kansas State University
Dept. of Mechanical Engineering
Manhattan, Kansas

4. Minnesota Mining and Manufacturing Company
St. Paul, Minnesota
Nelson Jonnes

5. Penn State University
University Park, Pennsylvania
E. R. Buskirk

6. Taylor Diving and Salvage Co.
Belle Chasse, Louisiana
Peter Erickson

7. The London Hospital
Whitechapel Road
London, England
William Keatings

8. U.S. Army Research Institute of Environmental Medicine
Natick, Massachusetts

9. U.S. Navy Submarine Development Group One
San Diego, California
Paul Linaweaver

10. University of California
San Francisco, California

11. University of California
    Santa Barbara, California
    S. Horvath

12. University of Miami
    Miami, Florida

13. University of North Dakota
    Grand Forks, North Dakota
    Thomas Akers

14. Westinghouse Ocean Research and Engineering Center
    Annapolis, Maryland
    W. J. O'Neill

XIV. CONCLUSION

The lack of adequate thermal protection has been and continues to be a major obstacle to achieving the goals of many diving operations. Thermal conditions faced by divers may not be acute or life-threatening, but they are often serious enough to reduce the amount of productive bottom time, which is ultimately the goal of every operation. Protecting lives is certainly foremost in any program, but thermal stress greatly affects diving operations in the range which precedes this critical level. Cold reduces overall efficiency and effectiveness, increases operating time, and in some situations, causes the mission itself to be aborted. The ultimate goal of any diving operation, regardless of the sophistication or impressive array of surface support, is how much time the diver spends on the bottom. If the diver is only partially effective because of cold, the entire operation is only partially effective.

Thermal protection requirements are widespread and nearly universal: saturation divers in helium environments, arctic divers breathing air, lockout divers, bell divers, and divers changing ship propellers in 15 feet of water are all affected to one degree or another by cold. Many contractors, and even supervisors fail to appreciate what being cold actually means: the diver is uncomfortable, inefficient, and in danger. Everyone involved in operational diving should become familiar with the causes, effects, and possible results of thermal stress.

This report has pointed to the research needed to answer the most pressing problems in this area. Until we have the necessary analytical tools and procedural techniques, we can only emphasize the severity of the problems of thermal stress in diving, and hope for continued progress in the fight against one of the biggest problem faced by divers today: cold.

COMPRESSION AND DECOMPRESSION PROTOCOLS

Part #2T

National Plan for the Safety and Health of Divers in their Quest for Subsea Energy

Produced by:

Robert W. Hamilton, Jr., Ph.D. (Chairman)
President, Tarrytown Labs, Ltd.
Tarrytown, New York

E. E. P. Barnard, M.D., Ph.D.
Dept. of Medical Director General (Navy)
Ministry of Defense, London, England

Peter B. Bennett, Ph.D.
Co-Director, F. G. Hall Environmental Research Laboratory
Director, Diving Research Program
Duke University Medical Center
Durham, North Carolina

H. V. Hempleman
Superintendent
Royal Naval Physiological Laboratory
Alverstoke, Hants, England

Brian A. Hills, Ph.D.
Chief, Hyperbaric Physiology Section
Marine Biomedical Institute, University of Texas
Medical Center
Galveston, Texas

Russell E. Petersen, Ph.D.
Supervisor, International Decompression Data Bank
Institute for Environmental Medicine
University of Pennsylvania
Philadelphia, Pennsylvania

Kent Smith, D.V.M., Ph.D.
Director, Hyperbaric Program
Virginia Mason Foundation for Medical Education and Research
Seattle, Washington

C. H. Hedgepeth (Advisor)
Operations Manager, Ocean Systems, Inc.
A. D. C. Representative
Reston, Virginia

TABLE OF CONTENTS and Organization for part 2T

Compression and Decompression Protocols

I. INTRODUCTION 1

II. PRESENT POSITION (DECOMPRESSION).......................... 1

A. Air Diving

B. Mixed-Gas Diving

1. Short Duration (Bounce) Diving
2. Medium Duration Diving
3. Saturation Diving

III. PRESENT POSITION (COMPRESSION) 3

IV. RESEARCH REQUIREMENTS 3

A. Compression Protocols

B. Decompression Protocols

1. Data Collection
2. Basic Physiology
3. Training
4. Decompression Sickness
5. Emergency Decompression Procedures

V. PRIORITIES 6

A. Research

B. Practical

VI. LABORATORIES INVOLVED IN DECOMPRESSION RESEARCH 7

I. INTRODUCTION

As world energy requirements increase, the search for sources of energy becomes more pressing. Much of this energy will come from offshore sources, many of them located at great depths. Exploiting these resources will require undersea work, some of which must be undertaken by divers. The health and safety of these divers must be protected to the best of our ability.

To work freely underwater, a diver must breathe gases at raised pressures. His body tissues absorb excess amounts of dissolved gas during this process, and it is essential that his tissues be cleared of this excess gas without causing any ill effects. Unless the dissolved gas absorbed at raised pressures is excreted in a safe manner, the diver will suffer from one or more forms of decompression sickness. Decompression sickness can appear immediately, in acute form, or it can occur many years later in chronic form.

The problems of placing a man under raised pressure of breathing gas (compression) and safely returning him to normal air pressure (decompression) are of primary importance to the success of underwater work.

There is general agreement that the majority of decompression tables are unsatisfactory and require modification. The rapid expansion of the oil industry demands the development of safe and economic compression and decompression procedures. There are many basic problems to resolve before this can be achieved.

II. PRESENT POSITION (DECOMPRESSION)

A. Air Diving

Air is the most commonly used breathing medium in diving, but it cannot normally be used safely at depths greater than about 180 fsw. Two principal factors limit the use of air beyond this depth: respiratory embarrassment caused by the increased density at such pressures, and the narcotic properties of raised partial pressures of nitrogen. The substitution of the nitrogen in air by the less dense and nonnarcotic helium overcomes these two major problems, but the use of helium introduces other problems, particularly HPNS, body heat loss and voice distortion.

Most air diving is presently done using the U.S. Navy Standard Air Tables, but the inadequacies of these tables have resulted in their empirical modification by various diving companies. Other air diving decompression tables are available, but their safety records are not; it is therefore difficult to comment on their usefulness.

Inadequate decompression after a dive or other exposure to high pressure will cause decompression sickness. The presence of separated gas in some relevant tissue(s) of the body is generally held to be the primary cause of acute decompression sickness. Acute decompression sickness can be manifested in a variety of ways, ranging from itching of the skin, to limb pains (bends), paralysis, audio-vestibular involvement, or collapse and death. The etiology of the chronic forms of decompression sickness, such as dysbaric osteonecrosis, is far from understood,* and the medical management of these various forms of decompression sickness are described elsewhere.** It is only necessary to state here that the vast majority of cases of acute decompression sickness are satisfactorily treated by recompression therapy. The principal therapeutic tables in worldwide use are those given in the U.S. Navy Diving Manual; they are also described by Kidd and Elliott.***

B. Mixed-Gas Diving

The situation in mixed-gas diving is even more difficult; decompression tables are available from several sources. Many tables which have been used extensively are not available for general scrutiny and use because of their commercial and confidential nature. At the present time, there are no satisfactory and publicly available helium-oxygen diving tables.

A variety of profiles designed to meet different underwater work situations are presently in use.

1. Short Duration (Bounce) Diving

These profiles are designed for minor repair, adjustment, inspection, and typical support tasks, where the diver returns to atmospheric pressure on completion of the assigned work. Working time on the bottom is usually limited to 15-30 minutes. This diving mode is characterized by relatively short decompression.

2. Medium Duration Diving

Here the dives have bottom times ranging from 1-2 hours. They involve a longer decompression time, and may require decompressions very similar to those used in saturation-type profiles.

---

*See Report #2.

**See Report #5T

***D. J. Kidd and D. H. Elliott. Decompression disorders in divers. In: The Physiology and Medicine of Diving and Compressed Air Work, edited by P. B. Bennett and D. H. Elliott. (London: Bailliere Tindall, 1975).

3. Saturation Diving

In prolonged work at a constant depth, the diver's tissues acquire the maximum amount of dissolved gas, and the decompression is therefore not dependent on further increases in bottom time. While living at this saturation pressure, the diver is sometimes required to make short duration dives to much greater depths. This mode is often called saturation-excursion diving, and it may require special compression/decompression procedures.

Decompression sickness encountered in mixed-gas diving takes the same forms as noted above. However, it is not uncommon for acute decompression sickness to occur while the divers are still under pressure, and there is also a marked tendency toward involvement of the audio-vestibular system, which sometimes leads to permanent damage. The U.S. Navy's therapeutic recompression tables cannot provide adequate security in these circumstances, and consequently numerous 'ad hoc' procedures are being used.

III. PRESENT POSITION (COMPRESSION)

The chief advantage of a faster compression rate is that it reduces the amount of time required for the operation. The choice of compression rate to a working depth is presently constrained by such factors as the heat generated, the noise level of the inrushing gas, and, more importantly, by the onset of HPNS and arthralgia.*

IV. RESEARCH REQUIREMENTS

A. Compression Protocols

There are physiological limitations to the rate of compression, particularly in oxygen-helium dives deeper than 500 fsw. To optimize the rate of compression it is necessary to obtain a better understanding of the effects of gas exchange and hydrostatic pressure in a rapidly changing environment. In view of the subtle nature of many of the physiological end points involved, research which uses man as the subject will yield the most pertinent information. Assembling the knowledge necessary to an understanding of these problems will permit the calculation of protocols for compression rates which are compatible with the safety and health of the diver. Engineering solutions to eliminate the problems of heat and noise generated during compression must also be found.**

---

*HPNS is considered in greater detail in Report #12.

**The correlation between noise level and hearing loss in divers is considered in Report #1.

B. Decompression Protocols

Decompression protocols must move beyond reliance on large-scale trial and error procedures. Methods based on sound knowledge of basic principles must be developed.* Until such basic information is available, it would be premature to impose standard procedures or decompression tables on commercial diving, especially for deep mixed-gas diving.

1. Data Collection

A major problem in any epidemiological study is the difficulty of recording relevant parameters from open-sea commercial dives. Attention must be directed toward constructing suitably robust and convenient monitoring devices for recording at least the voice, dive profile, pressure and oxygen level as a function of time, and as many additional factors such as gas composition, heart rate, and breathing rate as possible.

There is a need for a central repository to record data from both experimental and accurately recorded operational dives, and an identified group of laboratories where protocols may be adequately tested. Decompression tables should not be issued for general use at sea without suitable preliminary testing, both in the laboratory and at sea.

Workshops or other means for encouraging coordination, cooperation, and the exchange of information between the various laboratories and companies involved in developing decompression schedules need to be devised.

2. Basic Physiology

Report #7 discusses the need for a greater understanding of tissue gas exchange, and the various factors which influence it. The studies which are recommended in that report are fundamental to the formulation of safe and efficient protocols for the following range of diving circumstances: 1) simple air or oxygen-helium dives; 2) dives employing mixed gases, either on the bottom or during decompression; 3) repetitive dives; 4) saturation-excursion dives; and 5) surface decompression procedures.

Because of the many variables involved, it is likely that there may be more than one safe and efficient way for decompressing a diver from a given depth. As many research approaches as possible should therefore be entertained. With the variation in tasks, equipment, and logistics at a given dive site, no single decompression schedule will be suitable for all situations. Knowledge of the principles involved in safe decompression in a variety of different circumstances, e.g., with and without exercise during decompression, and with varying environmental temperatures, is urgently needed.

---

*See Report #7 for details.

In recent years, various means, chiefly those using Doppler and other ultrasonic methods, have been used to detect bubbles in the blood and tissue which may be responsible for decompression sickness. There is a need for further development and evaluation of these methods.*

An understanding of the body changes which accompany adaptation to the bends is important, as these body changes could be either helpful or harmful to the diver.

The use of pharmacological agents in ensuring speedy and safe decompression should be investigated. This research would also be helpful in problems related to the treatment of decompression sickness.

Research is urgently needed to establish oxygen tolerance levels, to determine the effects of exposure to high levels of oxygen, and to find means of extending man's tolerance to this gas. In addition, there is some evidence that oxygen's role in decompression and decompression sickness may be greater than previously thought. An evaluation of the effects of oxygen on the development and resolution of decompression sickness would have great practical significance for the diving industry. Methods which will allow decompression profiles to be adjusted to account for differences in oxygen content should be developed. Different field conditions require different methods of handling oxygen; some cases require that a constant fraction or percentage of oxygen be maintained, while others demand a constant partial pressure. Practical field procedures which will ensure the safety and health of divers depend on basic research into these questions.**

3. Training

There is a need for training courses in practical decompression procedures, such as chamber control and life support systems, for divers, diving superintendents, chamber operators, medical and paramedical personnel, and researchers. Such training will not only increase the safety of diving but its efficiency as well.***

---

*See Report #7 for details.

**See Report #10.

***This is described in further detail under Report #5 and Report #5T of this National Plan.

4. Decompression Sickness

Methods for the early detection of the onset of decompression sickness are needed. This is particularly true for disturbances in audio-vestibular functioning. As noted earlier, most bubble detection work is based on ultrasonic principles, but work on other forms of detection should be encouraged.

There is considerable disquiet over the possibility that apparently safe decompression schedules, i.e., those which produce no overt forms of decompression sickness, could nevertheless be responsible for significant long-term changes in certain body processes. It is well established that there are hematological changes following such dives, and it is a matter of some urgency to ensure that such changes do not have short- or long-term sequelae harmful to the diver, e.g., dysbaric osteonecrosis.

Treatment of deep helium decompression sickness will require a knowledge of safe therapeutic decompression rates at different dive depths; this could be particularly important for the traumatized diver.

The efficacy of various forms of medical management under pressure also requires attention.*

5. Emergency Decompression Procedures

It may be necessary in an emergency to decompress a diver or group of divers at an accelerated rate, either for medical purposes or for operational reasons. Procedures to do this in the best possible way, with a set of selective risk factors, are urgently needed.

V. PRIORITIES

Choosing between basic research priorities and practical needs is difficult, for they are irrevocably interlocked. The committee feels strongly that funding of both basic and applied research must be concurrent. Though we appreciate the need for practical work which will permit safer and more effective diving now and in the immediate future, we recognize that most present decompression problems are caused by a serious lack of basic information. The committee unanimously urges that funding be more heavily weighted toward basic research so that progress can be based on firm foundations.

Similarly, the priorities given the sub-topics below were not meant to be rigid. There is considerable overlap between these priorities and problems discussed by other committees of this project.

---

*See Report #11 for details.

Even in a period as short as two years, some of these priorities could change, either because of a sudden breakthrough in knowledge, or the development of an unexpected problem which affects the safety and health of divers and requires an immediate solution.

A. Research

1. Physics and physiology of decompression and decompression sickness, and investigation of sub-clinical sequelae

2. Factors affecting compression and decompression

   a. Environmental
   b. Human

3. Monitoring of physical and physiological parameters of decompression and decompression sickness

B. Practical

1. Continuation of development of compression and decompression procedures

2. Training

3. Data collection, information exchange, and epidemiology

4. Diver monitoring

5. Medical treatment and emergency decompression

VI. LABORATORIES INVOLVED IN DECOMPRESSION RESEARCH

Due to the mobility of trained staff and the scarcity of available funding, it is very difficult to say with assurance whether these laboratories will maintain their current position in decompression work. To the best of the committee's knowledge and belief, however, current status and categories of laboratories is as follows:

A. Major laboratories with a substantial history and strong current interest in decompression.

1. F. G. Hall Environmental Laboratory, Duke University Medical Center, Durham, North Carolina
   1000 fsw, saturation, 6 divers, wet, altitude, 6 interlocking chambers, 4500 fsw animal (dog); full laboratory capability
   Gas transport, O_2 tolerance, monitoring, decompression and compression procedures, table testing, treatment.

   Peter B. Bennett

2. Institute for Environmental Medicine, University of Pennsylvania, Philadelphia, Pennsylvania
1800 fsw, saturation, 4 divers, wet, altitude, 4 interlocking chambers; 4500 fsw animal (monkey); USN certified; full laboratory capability; International Decompression Data Bank. Inert gas exchange, counter-diffusion, bubble formation, O_2 tolerance, computer modeling, decompression and compression procedures.

C. J. Lambertsen

3. Marine Biomedical Institute, University of Texas Medical Branch, Galveston, Texas
800 fsw, saturation, wet, 4 divers
Gas transfer and decompression theory, decompression meter development, bone necrosis, full laboratory capability.

Brian A. Hills

4. S.U.N.Y. at Buffalo, New York
5000 fsw, wet, 3 divers, altitude
Gas transport, gas exchange

Herman Rahn

5. Tarrytown Labs, Ltd., Tarrytown, New York
1000 fsw, dry only, saturation to 675 fsw, 2 divers, altitude, small animals to 5000 fsw, altitude
Table development, use of neon, nitrogen saturation-excursion, computer control and monitoring, strong commercial orientation.

R. W. Hamilton, Jr.

6. Taylor Diving and Salvage Co., Belle Chasse, Louisiana
2000 fsw, wet, saturation, 6 divers
Support staff, capable of expansion

Peter Erickson

7. Texas A&M University, College Station, Texas
600 fsw, large animals
Table development, hydrogen

William P. Fife

8. Virginia Mason Research Center, Seattle, Washington
1500 fsw, saturation, 2 divers; 400 fsw, animal (large); 1800 fsw, animal (small); full laboratory capability.
Table development, inert gas exchange and transport, decompression pathophysiology and bone necrosis, Doeppler monitoring

Kent H. Smith

B. Laboratories with current work or interest in decompression.

1. Beth Israel Medical Center, New York, New York
Shallow, small animal, chamber, altitude
Drug and hormone effects on decompression, bone necrosis

Chryssanthos P. Chryssanthou

2. Bowman-Gray Medical School, Wake Forest University, Winston-Salem, North Carolina
Small animal
Auditory-vestibular decompression sickness

James G. McCormick

3. Colorado State University, Fort Collins, Colorado
250 fsw, 10 divers, large animals, altitude
Altitude decompression

Peter Hall

4. Institute for Applied Physiology and Medicine
Seattle, Washington
300 fsw, 2 divers
Doeppler monitoring, gas transport

Merrill C. Spencer

5. St. Lukes Hospital, Milwaukee, Wisconsin
225 fsw, 8 divers
Treatment of decompression sickness, caisson work, inert gas transport

Eric P. Kindwall

6. University of Hawaii, Honolulu, Hawaii
   600 fsw, DDC on shore
   Sea trials, bubble formation

7. University of Rochester, Rochester, New York
   Animal chamber
   Pharmacological treatment of decompression sickness

   A. T. K. Cockett

C. Laboratories limited in facilities or orientation toward decompression, or those which are inactive at this time.

1. Harbor Branch Foundation, Fort Pierce, Florida
   2 lockout submersibles, 1500 fsw; 1000 fsw DDC, saturation, on R. V. Johnson
   Open-sea testing

2. Sea-Space Research, Harvey, Louisiana
   Chamber to be operational June 1976
   Commercial table computation, use of hydrogen

   Peter Edel

3. Scripps Institute of Oceanography, La Jolla, California
   No laboratory chamber
   Fundamental decompression theory

   Hugh Bradner

4. University of North Dakota, Grand Forks, North Dakota
   Extensive animal chamber complex
   Oxygen toxicity, chronic inert gas effects

   Thomas Akers

5. University of Southern California at Avalon, California
   225 fsw, 4 divers
   Treatment, telemetry, open-sea monitoring

   Andrew J. Pilmanis

6. Westinghouse Ocean Research and Engineering Center, Annapolis, Maryland
   1500 fsw, wet, saturation, 3 divers

   W. J. O'Neill

7. Wrightsville Marine Biomedical Laboratories, Wilmington, North Carolina
   600 fsw, animal (large); 3200 fsw, animal (gill breathers)
   Compression effects, HPNS

   Ralph W. Brauer

D. Military laboratories or facilities.

1. Naval Coastal Systems Laboratory/Naval Experimental Diving Unit, Panama City, Florida
   2500 fsw, saturation, wet, large staff; full laboratory capability
   Decompression table development (equipment and task oriented)

   W. H. Spaur

2. Naval Medical Research Institute, Bethesda, Maryland
   3300 fsw, saturation to 2200, wet 2200 (due 1978), altitude; full laboratory capability
   Basic research in support of diving operations

   Large staff

3. Naval Submarine Medical Research Laboratory, Groton, Connecticut
   300 fsw, 3 divers, dry; full laboratory capability
   Nitrogen saturation and saturation, excursion diving to 300 fsw

   Claude Harvey

4. USAF School of Aerospace Medicine, Brooks Air Force Base, San Antonio, Texas
   200 fsw, 4 divers, 2 chambers, altitude
   Treatment of decompression sickness, training of physicians

   Jefferson C. Davis

5. U.S. Navy Submarine Development Group One, San Diego, California
Mark I Deep Diving System (1000 fsw DDC) on MV ELK RIVER
Sea trials

Paul Linaweaver

REFERENCES

Because of the nature of the technology and the type of research involved, the committee felt that a general literature review was unwarranted. For more information about decompression, the following sources contain sufficient material.

1. Bennett, P. B., and D. H. Elliott. 1975. The Physiology and Medicine of Diving and Compressed Air Work. 2nd ed. London: Bailliere Tindall.
2. Hamilton, R. W., Jr. (in press). Development of decompression procedures for dives in excess of 400 ft. Duke University Medical Center Workshop. Bethesda, Md.: Undersea Medical Society.
3. Hong, S. K., (Ed.) (in press). Intern. Symp. Man in the Sea. July 13-15, 1975. Bethesda, Md.: Undersea Medical Society.
4. Lambertsen, C. J., (Ed.) 1967. Proc. 3rd Symp. Underwater Physiol. Baltimore: Williams and Wilkins.
5. Lambertsen, C. J., (Ed.) 1971. Proc. 4th Symp. Underwater Physiol. New York: Academic.
6. Lambertsen, C. J. (Ed.) (in press). Proc. 5th Symp. Underwater Physiol. Washington, D.C.: Fed. Am. Soc. Exp. Biol.
7. Shilling, C. W., and M. F. Werts. 1971. An Annotated Bibliography on Diving and Submarine Medicine. London: Gordon and Breach.
8. Shilling, C. W., and M. F. Werts. 1973. Underwater Medicine and Related Sciences. A Guide to the Literature. Vol. I. New York: IFI Plenum.
9. Werts, M. R., and C. W. Shilling. 1975. Underwater Medicine and Related Sciences. A Guide to the Literature. Vol. II. New York: IFI Plenum.

SYSTEMS DESIGN CRITERIA

Part #3T of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Bruce C. Gilman (Chairman)
Executive Vice President & Managing Director
Perry Oceanographics, Inc.
Riviera Beach, Florida

Anthony Gaudiano
Vice President, Engineering
Taylor Diving & Salvage Company
Belle Chasse, Louisiana

William J. Giannotti
Operations Coordinator
Ocean Systems International, Inc.
Reston, Virginia

Paul G. Linaweaver, Jr.
Captain, Medical Corps, U.S. Navy
Submarine Development Group One
San Diego, California

TABLE OF CONTENTS and Organization for part 3T

Systems Design Criteria

I. INTRODUCTION 1

II. RESEARCH RECOMMENDATIONS 3

III. CONCLUSION 6

I. INTRODUCTION

There has been an increasing emphasis on the exploration and exploitation of the world's offshore oil and gas resources during the last decade, and the demands made on the commercial diving services industry, which supports the offshore oil and gas industry, have grown accordingly. The search for oil and gas is worldwide, which means that the diving industry has had to dive deeper, in a greater variety of environments, to perform an increasingly large number of tasks. These tasks have tested both men and equipment, and generated a host of problems which have to be solved.

This committee believes that the purposes of the National Plan are best served by a systems approach which emphasizes components in the design criteria for diving systems, rather that a total systems design study. The requirements which we have outlined in this report are therefore operationally oriented, and determined and designed with the diving mode, the particular job, and the equipment actually in use in mind: the requirements for exploration/production drilling operations are not the same as those for pipe-line construction or surface-support diving activities. We have restricted our systems design criteria to the sub-component, materiel, and technological levels.

The committee identified the following major categories, after reviewing the literature and the experience of the various committee members:

A. Diving Support Equipment
B. Shallow Surface Diving Equipment
C. Deep Surface Diving Equipment
D. Short-Duration Bell Systems
E. Saturation Bell Systems
F. Submersibles
G. Habitats
H. Research Facilities
I. Rescue and Escape

A. Diving Support Equipment

This category generally includes the auxiliary and support systems used in commercial diving.

1. Gas Supply Systems
2. Gas Booster Compressors
3. Gas Mixers
4. Gas Reclamation Systems
5. Air Systems
6. Environmental Conditioning Systems
7. Hot Water Systems
8. Communication Systems
9. Handling Systems

B. Shallow Surface Equipment

Includes normal surface, SCUBA, and tethered air diving operations using either hard hat or shallow-water gear. This mode is generally not used beyond 170 fsw.

C. Deep Surface Equipment

This equipment is used in surface-tethered mixed-gas diving operations beyond 170 fsw and is not usually used beyond 300 fsw.

D. Short-Duration Bell Systems

Bell diving systems generally consist of a diving bell, which is the nucleus of the system, and a deck decompression facility. Control vans, auxiliary equipment, and handling systems complete the equipment requirements for bell diving systems. These systems are generally small in size, light in weight, and portable. Decompression periods are relatively short and do not normally include saturation. This mode is used primarily for short excursions to 600 fsw.

E. Saturation Bell Systems

Saturation bell systems are basically similar to short-duration bell systems, but are larger, heavier, and contain more complete analysis and environmental control systems. They generally allow saturation and saturation decompression of large crews (2-20 men), and are used principally to support construction, which may be shallow but require long work periods, or exploration/drilling in deep waters, which requires lengthy decompression.

F. Submersibles

This category includes untethered free-swimming submersibles which allow diver lock-out/lock-in operations or dry transfers to subsea wellheads at atmospheric pressure. Diver lock-out submersibles can be considered as free-swimming diving bells; they require surface deck decompression facilities similar to those required by bell diving systems.

G. Habitats

The habitats considered by this committee include ambient pressure types, such as the underwater dry welding chambers used for pipe-line construction, and research laboratories such as the Perry Hydro Lab. The 1-ATA dry wellhead enclosures such as those provided by Lockheed Petroleum and Seal Petroleum are included in the habitat category.

H. Research Facilities

This category includes government, institutional, and private hyperbaric research facilities which are used to simulate wet or dry hyperbaric conditions. These facilities are used to gather data on men and equipment in hyperbaric conditions. They resemble the deck decompression portions of bell diving systems, but are highly instrumented and controlled, and generally have the capability to simulate in situ (wet) conditions.

I. Rescue and Escape

This category deals with the equipment, methods, and procedures required to rescue or allow escape of personnel trapped in a subsea environment or during decompression on an endangered vessel. It includes self help and external means of rescue.

II. RESEARCH RECOMMENDATIONS

One of the requirements which became evident to the panel was the need for a comprehensive and thorough compilation and index of all literature in this sub-field. Much work on systems design has been done by government, institutions, and private groups. This information is urgently needed by diving systems' designers to allow the industry to take advantage of the millions of dollars and thousands of hours already spent on these problems. A literature search and compilation would make research in the following areas considerably easier.

Our research recommendations for design systems are arranged in order of priority.

A. Electrocution Hazards of Underwater Electrical Equipment

The underwater electrocution hazards connected with the use of alternating and direct current need to be studied. Divers are presently working with equipment which has higher energy levels than earlier underwater equipment. A study to determine the best type of system for both alternating and direct current is needed.

B. Contaminant Levels for Compressed-Air Supply Systems

We urge that studies of carbon monoxide, ozone, NO_x, SO_x, H_2S, and other atmospheric contaminants be made to determine allowable levels of these contaminants for compressed-air supply systems, and that these studies be related to background ambient levels of these contaminants. Compressed-air systems should be studied using dose-response curves, e.g., concentration/depth/exposure, synergistic/antagonistic effects, effects of pressure, and the partial pressure of other gases.

The committee believes that the carbon monoxide levels for divers' breathing gas have been arbitrarily set without actual testing. For example, the level of carbon monoxide established for diving compressed-air systems is less than the level of carbon monoxide which prevails in many metropolitan areas, e.g., Chicago, 0-44 parts per million, or New York, 0-54 parts per million. If the recommended purity standards for divers were followed, no wharf work could be done in such metropolitan centers.

C. Standards for Personal Diving Equipment

At present, personal diving equipment, such as masks and helmets, is marketed without being tested for safety. The committee recommends that a study of performance specifications, including flow rates, pressure drops, and endurance, be made to establish guidelines for standards for this type of equipment. Standards need to be established; all personal equipment should then be tested against these standards, and it should be mandatory that the results of such testing be affixed to all personal diving equipment.

D. Self-Contained Power Supplies for Submersibles and Habitats

Studies directed toward the development of self-contained power supplies for underwater use are urgently needed. Power supplies conventionally used in diving have only short-duration capacity, and permit only relatively short bottom times in emergency situations. The capacity to deliver heat to divers and compartments, particularly to lock-out submersibles, is at present very limited.

Studies on self-contained power supplies should be three-pronged: 1) they should focus on increasing the capacity of power supplies in current use; 2) they should ensure that systems which are presently in the developmental stage are designed with increased power capacity in mind; and 3) they should be directed toward developing new concepts which will meet underwater requirements for power supplies.

E. Physics and Effects of Sound Transmission on Hearing in Hyperbaric Conditions

Detailed research is needed on the basic physical mechanisms and the effects of sound transmission on hearing in the underwater environment. The development of instruments to measure sound levels, including calibration techniques which can be used at increased ambient pressures and in unusual gaseous environments, depends on the results of this type of research. At present, there is no evidence linking acoustic trauma to sound levels. The effects of many factors found in the hyperbaric environment, such as the damping effect of dense gases, and the shift from air to bone conduction of sound, need to be evaluated in relation to allowable noise levels. Concern for the conservation of the diver's hearing demand that such studies be undertaken.

F. In Situ Gas Analysis Instrumentation

Instruments for analyzing gases to measure the composition of hyperbaric atmospheres are needed. At present, atmospheric monitoring is limited to the analysis of oxygen, carbon monoxide, carbon dioxide, and trace contaminants in decompressed gas; in situ analysis at pressure includes the following methods: 1) oxygen, by the electrogalvanic method, which is excellent; 2) modified pH electrode analysis of carbon dioxide, which is inadequate; and 3) analysis of carbon dioxide and carbon monoxide trace contaminants, by chemical tube analysis, e.g., Draeger, Kitagawa.

There is a need for new methods of measuring carbon monoxide, carbon dioxide, and other trace contaminants at the diving site, and this need will increase as saturation depths become deeper, and diving conditions, such as those found in lock-out submersibles and floor-based habitats, become more isolated.

G. Wire Rope Lubricants

Research is needed to determine the best methods and materials for lubricating wire ropes. Wire rope manufacturers recommend various methods and materials, depending on the brand and type of rope; this can be a critical matter, particularly if the rope in question is part of the life-support system, as in the case of a lift wire for a diving bell. Experience has shown that failures of wire rope in operational diving result from corrosion, which proper lubrication would prevent. Bell lift wires are often of the non-rotating variety, which makes lubrication more difficult. The lubricant should penetrate to the core of the wire, and it should be somewhat resistant to water.

H. Rescue of Divers Under Pressure

The committee urges that a study be undertaken to recommend the best types of rescue vehicles and methods of evacuating pressurized divers from offshore installations. Such a study should include design recommendations for 1-, 2-, 3-, and 4-man vehicles, methods of transport, such as helicopter, boat, or self-flotation under tow, and means of maintaining life support. It should also deal with methods of escape from underwater habitats, and should include a list of all available vehicles which could provide rescue in an emergency.

I. Human Factors Engineering

Saturation diving techniques, which require divers to spend long stays under pressure, are becoming more frequent as work depths increase. Divers often spend as many as 30 days under pressure, and this period may increase to 60 days within the next five years. We recommend that a study be made of the human factors which should be considered in the design of chambers and systems, based on data gathered by canvassing commercial diving contractors.

J. Methods for Avoiding Overlapping Frequencies in Diving

The committee recommends that a study be made to determine the best frequencies for wireless communications systems and rig positioning. Recently, there have been problems when the same frequency was used for the emergency communication system on a diving bell and for the rig locator system. International agreement on frequency assignments may be necessary to preclude mutual frequency interference.

K. Hyperbaric Facilities List

The NAVSHIPS Hyperbaric Chambers list should be updated to include all hyperbaric research facilities in existence or under construction. Such a list would be an aid to equipment manufacturers and operators who are looking for facilities to test their products or services.

III. CONCLUSION

Many of the problems identified in section II of this report have been recognized by the diving community, and effort has been directed toward solving some of the problems outlined above. The diving community has traditionally tended to be secretive about methods and equipment, for reasons of commercial interest. The formation of the Association of Diving Contractors has resulted in a more cooperative policy, especially in areas related to the safety and health of divers.

In light of these developments, we recommend that the Association of Diving Contractors undertake a preliminary survey of the diving companies, to determine whether any progress has been made which might be pertinent to solving the problems of operational diving which this report has outlined.

REFERENCES

1. American Society of Mechanical Engineers. Boiler and Pressure Vessel Code, Section 8.
2. Association of Diving Contractors. 1974. Manual of Safe Practices in Commercial Diving Operations.
3. Battelle Columbus Laboratories. 1973. Proc. 1973 Divers' Gas Purity Symp. U.S. Navy Supervisor of Diving, Naval Ships Systems Command Rept. 2-73.
4. Battelle Memorial Institute. 1970. Purity standards for divers' breathing gas. Battelle Memorial Institute Rept. 06-70.
5. Landreman, D., editor. 1970. Equipment for the Working Diver. Washington, D.C.: Marine Technology Society.
6. Linaweaver, P. G. 1975. Medical aspects of small submersible operations. Undersea Medical Society Rept. WS7-1-75.
7. Shilling, C. W., and M. L. Werts. 1973. Underwater Medicine and Related Sciences: A Guide to the Literature. N.Y.: Plenum.
8. Spalsbury, D., editor. 1974. The Working Diver - 1974. Symp. Proc. Washington, D.C.: Marine Technology Society.
9. U.S. Navy. United States Navy Supervisor of Diving. 1971. Directory of world-wide, shore-based hyperbaric chambers, Vol. I, II. Washington, D.C.: Dept. of the Navy.
10. Werts, M. L., and C. W. Shilling. 1975. Underwater Medicine and Related Sciences: A Guide to the Literature, Vol. 2. N.Y.: Plenum.

MONITORING TECHNIQUES

Part #4T of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Andre Galerne (Chairman)
President, International Underwater Contractors, Inc.
City Island, New York

Kenneth N. Ackles, M.D.
Chief, Pressure Physiology Group
Defense and Civil Institute of Environmental Medicine
Downsview, Ontario, Canada

Charles Duff
Manager, Medical Department
Taylor Diving and Salvage Co., Inc.
Belle Chasse, Louisiana

LCDR David Hall, MSC, USN
U.S. Navy Submarine Development Group One
San Diego, California

L. S. Linderoth, Jr.
Technical Director
Professor of Mechanical Engineering
F. G. Hall Environmental Research Laboratory
Duke University Medical Center
Durham, North Carolina

Merrill P. Spencer, M.D.
Director, Administration and Clinical Research Center
Institute of Applied Physiology and Medicine
Seattle, Washington

TABLE OF CONTENTS and Organization for part 4T

Monitoring Techniques

I. INTRODUCTION 1

II. ECONOMIC CONSIDERATIONS AND OPPORTUNITIES OF MONITORING 1

III. PHYSICAL MONITORING (PTV) 2

IV. PHYSIOLOGICAL MONITORING 2

A. Diver Safety Monitoring (DSM)

B. Decompression Adequacy Technique (DAT)

V. MONITORING OF THE WORKING DIVER 3

A. Non-Saturation Diving

1. Surface-supplied diving to 120 fsw
2. Surface-supplied diving beyond 120 fsw
3. Surface-supplied diving, using bells or habitats
4. Bell diving
5. Lock-in/lock out submersibles

B. Saturation Diving

C. Normobaric (1 ATA) Diving

D. Research Diving

VI. RESEARCH PRIORITIES 7

VII. CONCLUSION 7

VIII. LIST OF LABORATORIES CURRENTLY WORKING ON MONITORING 7

IX. REFERENCES 11

I. INTRODUCTION

Despite the hazards involved, men will continue to be exposed to the underwater environment as long as there are critical jobs to be done on the sea floor which machines cannot do. Though we know many of the events which cause underwater accidents and deaths, we seldom have sufficient information to take effective action to prevent future occurrences.

Divers endure a variety of environmental stresses, such as pressure, pressure changes, temperature extremes, and physical work loads. Monitoring devices which continuously record physical and physiological data while the diver is underwater must be designed with the type, degree, and risk of a particular operation in mind.* The use of monitoring devices will make diving a safer and healthier occupation. It is now possible to monitor the physical stresses to which a diver is subjected adequately, but there are some important physiological variables which need further research and technology.

This committee recommends both monitoring and recording procedures for various diving operations. These procedures would improve the safety of the diver, and would also provide factual information for subsequent analysis in case of accident. The progress which the aviation industry has made in safety, which should be instructive for the diving industry, has been due to two factors: 1) after a significant accident, recordings permit analysis of the key events leading up to the accident, and 2) an independent board of experts reviews these facts, and can, by recommendation, prevent a recurrence of similar accidents. We are particularly concerned because accidents in diving are often repetitive. We believe that diving accidents will continue to happen as long as we remain ignorant of the true causes of these catastrophes.

The committee considered many physical and physiological parameters whose monitoring and recording would be desirable. We have selected only those which are currently both important and feasible. We have also indicated priorities for future work to develop improved physical and physiological monitoring devices and techniques.

II. ECONOMIC CONSIDERATIONS AND OPPORTUNITIES OF MONITORING

Monitoring and recording present both problems and opportunities for the diving contractor. A certain amount of resistance may be expected from diving contractors and on-the-job personnel because monitoring techniques allow responsibility for human error to be assigned; questions of insurable liability are also more easily defined. The purpose of monitoring is not to punish human error, but to reduce it by controlling it. Monitoring and recording techniques also demand an investment in technology, equipment, maintenance, and labor which initially increases operating costs. However, the implementation of these recommendations will reduce future insurance and operating costs; automated monitoring and recording systems often save on labor, in addition to providing accurate and continuous records of important data. On-the-job safety has been a good investment in any industry, but it is especially so in diving. When diving accidents occur, they very frequently cause the dive to be aborted. A medium-sized semisubmersible drilling rig may cost $40,000 per day to run; a major decompression accident may stop work for several days or more. When this kind of liability is considered, the cost of monitoring and recording is insignificant.

---

*In this report, monitoring is defined as the continuous or periodic observation of physical or physiological data, and recording means the automatic and reproducible storage of this data.

III. PHYSICAL MONITORING (PTV)

The most fundamental factors, pressure, time, and voice (PTV), can be monitored without great cost in all present diving work. Pressure is responsible, directly or indirectly, for many of the incidents or accidents which take place. Since the effects of pressure vary over time, time references are essential. Monitoring of communications is also an important part of current safety procedures. Voice recordings of diving accidents usually include the sounds of compression, decompression, hatch closings, and respiration. More important, however, they usually indicate the diver's awareness of trouble.

PTV monitoring records can be examined immediately after an accident, near-accident, or incident, and they also often provide data on other physical and physiological factors which may have played a part in the incident. PTV recordings can be made without disrupting ongoing activities. This basic information would provide sufficient information to allow accurate diagnosis of the genesis, progress, and consequences of most diving accidents. We believe all commercial diving operations should be required to maintain and use PTV and, further, that deliberate destruction of such records be prohibited by law; only knowledge of the facts will make diving safer.

IV. PHYSIOLOGICAL MONITORING

As the risk of injury to the diver increases, the need to know more about his physiological condition becomes greater. In high-risk diving situations, we recommend the use of Diver Safety Monitoring.

A. Diver Safety Monitoring (DSM)

DSM consists of monitoring: 1) heart rate, which reveals the diver's response to stress in general, and exertion in particular; 2) respiration rate, which provides early warning signs of overbreathing, carbon dioxide toxicity, and anxiety; and 3) core and inhalation/exhalation temperatures, which indicate the diver's thermal balance.

Additional physiological measurements which are not currently practical, but which would clearly be beneficial in assessing the safety of the diver include: 1) breath-by-breath partial pressure monitoring of carbon dioxide and oxygen, which would permit analysis of metabolism and indicate equipment malfunction; 2) electroencephalogram, which would give evidence of HPNS and oxygen and carbon dioxide toxicity; 3) tremor, which also indicates HPNS; and 4) behavioral monitoring, to indicate the onset of stress and behavioral disorganization.

B. Decompression Adequacy Technique (DAT)

Another measurable physiological variable is the detection, using an ultrasonic device, of the formation of bubbles in the tissues and blood as a result of decompression. It is known that many cases of impending decompression sickness are indicated by the presence of bubbles in the blood and tissues.

V. MONITORING OF THE WORKING DIVER

The following recommendations for specific diving situations are grouped according to the type of equipment and the type of diving mode used. Table 4T-1 summarizes these recommendations.

Greater-than-normal risk confronts the diver in any dive where obstructed ascent, entanglement or other circumstances that might prevent safe escape, thermal extremes, natural phenomena such as weather, current, or hostile marine life, or experimental decompression profiles are encountered. In such circumstances, we recommend using Diver Safety Monitoring (DSM). The Decompression Adequacy Technique (DAT) should be used whenever experimental or non-verified decompression schedules, marginal decompression, or repetitive diving are necessary.

When pre-mixed gas is used, analysis of PO_2 must be performed prior to each dive. In cases where two or more inert gas components are used in a single mix, documentation of the proportions of inert gases must be available from the supplier on site, and such analysis must be legibly marked on each cylinder. When on-site mixing techniques are employed, calibration of the equipment with a gas of known O_2 proportion, or air, must be performed prior to each dive.

A. Non-Saturation Diving

1. Surface-supplied diving to 120 fsw using air or nitrogen-oxygen mixtures does not usually require monitoring. Such dives generally involve SCUBA gear or use mouthpieces, band masks, or hard hats. Time and pressure monitoring is beneficial and recommended. Voice monitoring is standard practice in surface-supplied diving.

2. Surface-supplied diving from 120 fsw to permissible limits, using air or mixed gas, should include mandatory recording

Table 4T-1. Type of monitoring recommended for various diving operations.

Type of Operation	DDC		PTC		Diver	
	Monitor	Record	Monitor	Record	Monitor	Record
Non-saturation surface-supplied to 120 fsw	-	-	-	-	Voice	
Non-saturation surface-supplied beyond 120 fsw	-	-	-	-	Voice DSM and DAT may be required in high-risk diving	PT
Non-saturation surface-supplied, using open-bottom bell or other submersible refuge	-	-	Voice	-	DSM and DAT may be required in high-risk diving	PTV
Non-saturation bell diving, or lock-out from submersible	PO_2	PTV Temperature	PO_2 PCO_2	PTV	DSM and DAT recommended	PTV
Saturation diving, using bell, DDC, habitat, or lock-out submersible	PO_2 PCO_2 Temperature Humidity	PTV PO_2	PO_2 PCO_2 Temperature	PTV	DSM and DAT recommended	PTV
Normobaric (1 ATA) diving, DDC or submersible	-	-	PO_2 PCO_2	Pressure (external)		Voice
Research	as required	PTV	as required	PTV	as required	PTV

DDC = deck decompression chamber; PTC = personnel transfer capsule;
Monitoring = periodic observation of physical and/or physiological parameters; recording = automatic reproducible storage of information; PTV = combined time, pressure and voice recording, keyed together; DSM = Diver Safety Monitoring of core temperature, inhalation temperature, heart rate, and respiratory rate; DAT = Decompression Adequacy Technique for detecting bubble formation in blood and/or tissue.

of depth and time, and voice communication monitoring. As depth increases, the diver's safety depends increasingly on his ability to return to the surface within certain time limits.

3. Surface-supplied diving which requires bell, habitat, or other refuge at ambient pressure, should have pressure, time, and voice monitoring and recording. Separate facilities for monitoring voice must be provided in the bell.

4. Bell diving, including that using a lock-out submersible, differs from surface-supplied diving because the diver can be protected from the environment, including the effects of pressure, for parts of the operation. This diving mode involves the use of a Deck Decompression Chamber (DDC), or Personnel Transfer Capsule (PTC or bell), in addition to other equipment.

Monitoring and recording pressure, time, and voice at the diver is mandatory at all times, as is recording pressure and time outside the bell when the bell is sealed and there is a pressure differential. Pressure monitoring inside the bell must be available to the bell and surface tenders. Monitoring of PO_2 and PCO_2 inside the bell should be available to the bell tender and topside support. The DDC must have facilities for monitoring PO_2, PCO_2, temperature and humidity, and for recording pressure, time, and voice. DSM and DAT are recommended in these operations.

5. Lock-In/Lock-Out Submersibles

It is clear that bell-diving requirements apply to the submersible with lock-in/lock-out capability; the diving compartment is considered as the PTC, and the submersible operator compartment, which remains at surface pressure, as topside control. A DDC on the support craft is obligatory for diver lock-out operation of a submersible. Transfer to and subsequent decompression within the DDC takes place in the same fashion as with a PTC and DDC.

B. Saturation Diving

Saturation diving invariably involves the use of at least one DDC, and a PTC is generally used for transportation to and from the work level. Divers may be saturated at the pressure/depth of the work, or at an intermediate level; if an intermediate stage is used, they make excursions down to the work site. Excursion diving, up- or downward, should only be done using approved or verified tables.

At the DDC, pressure, time, and voice communications are monitored and recorded. Partial pressures of oxygen and carbon dioxide must be monitored, in addition to the temperature of the chamber atmosphere. Monitoring humidity is optional. The Diver Safety Monitoring (DSM) and Decompression Adequacy Technique (DAT) are recommended for this mode. As the reliability of instrumentation increases and equipment costs are reduced it may be important to use these procedures on all dives. Other physiological parameters, including EEG, tremor, and behavioral indicators, may be desirable as dives approach 1000 fsw and beyond.

Monitoring requirements for use on the PTC are identical to those required on the DDC, with the exception of humidity monitoring.

C. Normobaric (1 ATA) Diving

Closed-cabin diving includes observation dives in a PTC, submersible inspections of underwater phenomena, and any other operation where man is protected from external pressure during the entire course of the dive. The various 1-ATA diving systems extant today are: 1) observation bell (bathysphere); 2) dry submersible, which does not have or utilize lock-out capability; 3) 1-ATA diving suit; and 4) submersible or bell, servicing a 1-ATA chamber on the sea floor, using a dry personnel transfer system.

In this mode, the inhabitants of the submerged chamber do not become divers unless a catastrophe occurs: if the chamber fails to resist external pressure, or incorrect procedures cause internal pressurization, or entanglements or other operational problems oblige the inhabitants to attempt escape by swimming to the surface.

If the submersible or bell locks onto a chamber situated on the sea floor to effect a dry personnel transfer, there is additional risk. In a subsea wellhead completion, the chamber contains an inert gas, such as nitrogen, which will not support life or combustion; the service technician must carry life-support gas with him. During the transfer processes, the service technician must also keep the atmosphere of the submersible or bell uncontaminated by the atmosphere of the subsea completion. The environment in which he works is thus hostile, even though pressure is not a problem. The techniques and equipment for this mode are new and the risks involved have not been assessed.

The committee recommends that pressure, time, and temperature be monitored and recorded, either at the submersible operator's cabin or on the deck of the support vessel, in all types of closed-cabin diving.

D. Research Diving

Research dives are usually well monitored and documented. The goals of research dives vary greatly; the data obtained from research dives are also varied. Whatever the purpose of the research dive, there are basic parameters which must be monitored and recorded. Pressure, time, and voice recordings should be required in the DDC, PTC, and on the diver. Other parameters, such as PO_2, PCO_2, temperature, and humidity, may be required, depending on the type of diving operation.

VI. RESEARCH PRIORITIES

The committee believes that the following techniques and technology must be developed to ensure the adequate and accurate monitoring and recording of essential physical and physiological data for use in operational diving. The list of research recommendations is arranged in order of priority.

A. Engineering research to monitor the partial pressure of carbon dioxide at the diver is urgently needed.

B. The Diver Safety Monitoring Package (DSM), including core and inhalation/exhalation temperatures, heart rate, and respiratory rate, is not yet in routine use commercially. Two types of DSM are produced, using either hard-wire or acoustic telemetry.

C. The Doppler Decompression Adequacy Technique is well advanced in testing, but for extensive use simpler application and standardized interpretation are required.

D. Equipment which will allow breath-by-breath PO_2 and PCO_2 analysis and provide a continuous, reliable, and instantaneous readout of O_2 and CO_2 inhalation and exhalation while under pressure is needed.

E. There is a demand for a compact and comprehensive physiological data acquisition system.

VII. CONCLUSION

We recognize that legislative efforts in a rapidly progressing industry are often obsolete before they are written, and that regulations will not replace common sense and good planning. The recommendations we have made in this report will be superseded as technology changes; the basic principle, that monitoring and recording the facts is the only way to obtain the information necessary to improve the safety and health of divers, will remain with us as long as divers work under the sea.

VIII. LIST OF LABORATORIES CURRENTLY WORKING ON MONITORING

Facilities and investigators with experience in the special problems of monitoring the diver's environment are listed below by type of research specialization. This list is not comprehensive, and should be used accordingly.

Decompression Monitoring

1. Boston University
   Boston, Massachusetts

   Stuart Mackay

2. Institute for Applied Physiology and Medicine
Seattle, Washington

Merrill P. Spencer, M. R. Powell

3. Marine Biomedical Institute
University of Texas Medical Branch
Galveston, Texas

Brian A. Hills

4. Naval Submarine Medical Research Laboratory
Groton, Connecticut

Karl E. Schaefer

5. University of Washington
Applied Physics Laboratory
Seattle, Washington

Dean P. Haugen

6. Virginia Mason Research Center
Seattle, Washington

Kent H. Smith

7. University of Lund
Institute of Aviation Medicine
Lund, Sweden

C. E. G. Lundgren

Diver Monitoring

1. Commercial Diving Center
Wilmington, California

James T. Joiner

2. Defense and Civil Institute of Environmental Medicine
Downsview, Ontario, Canada

Kenneth N. Ackles

3. Gaustad Sykehus
   Oslo, Norway

   Carl W. Sem-Jacobsen

4. Harbor Branch Foundation
   Fort Pierce, Florida

   E. A. Link, Roger Cook

5. Naval Coastal Systems Laboratory
   Panama City, Florida

   Ed Sharp

6. Naval Medical Research Institute
   Bethesda, Maryland

   Lee Kurlansik, Anthony D'Addario

7. U.S. Navy Submarine Development Group One
   San Diego, California

   David Hall

8. University of Southern California
   Avalon, California

   Andrew J. Pilmanis

9. Webb Associates
   Yellow Springs, Ohio

   Paul Webb

Monitoring Equipment and Techniques

1. Andros, Inc.
   Berkeley, California

   Kevin Williams

2. Biomarine Industries
   Devon, Pennsylvania

   Fred Parker

3. Emergency Care Research Unit
   Philadelphia General Hospital
   Philadelphia, Pennsylvania

   Alan Slater

4. Environmental Systems Division
   General Electric
   Philadelphia, Pennsylvania

   Cliff Zierdt, Larry Lady

5. International Biophysics
   Irvine, California

   Hideo Watanabe

6. Tarrytown Labs, Ltd.
   Tarrytown, New York

   David J. Kenyon

7. University of New Hampshire
   Durham, New Hampshire

   H. Richard Skutt

REFERENCES

1. Arctic IV: exploring the polar frontier. 1974. Faceplate 5:28-30.
2. Bachrach, A. J., and M. E. Bradley. 1973. Early indications of behavioral and physiological dysfunctioning in deep dives. 3rd Undersea Med. Soc. Workshop. Bethesda, Md.: Undersea Med. Soc.
3. Bachrach, A. J., D. R. Thorne, and K. J. Conda. 1971. Measurement of tremor in the Makai range 520-foot saturation dive. Aerospace Med. 42:856-860.
4. Bachrach, A. J., and A. Findling. 1974. Microtremor. Biomedical research and underwater breathing apparatus evaluation dives 10 to 1600 feet (Abstract). U.S. Navy Exp. Diving Unit Rept. NEDU-23-74.
5. Baldwin, H. A., D. L. Brumbaugh, and D. E. Hall. 1969. Biotelemetry techniques. Preliminary Tech. Rept. Tucson, Arizona: Sensory Systems Lab.
6. Bevan, J. 1970. Observations of the human AER and CNV during an exposure to a hyperbaric air environment. UK Roy. Nav. Physiol. Lab. Rept. 8-70.
7. Braithwaite, W. R. 1974. Biomedical instrumentation for the 1973 EDU dive to 1,600 feet. U.S. Navy Exp. Diving Unit Rept. 6-74.
8. Carpenter, E. P., and T. S. Cooke. 1968. Logistic and surface support. Undersea Technol. 9:46-47.
9. D'Aoust, and H. T. Swanson. 1974. Bubble-free decompression of blood samples. J. Appl. Physiol. 37:589-591.
10. Deep Submergence Systems Project Office, U.S. Navy. 1968. Physiologic evaluation of Sealab II. Med. Ann. D.C. 37:313-315.
11. Diver instrumentation. 1971. TRW Systems Group Rept. TRW-16416.002.
12. Evans, A., E. E. P. Barnard, and D. N. Walder. 1972. Detection of gas bubbles in man at decompression. Aerospace Med. 43:1095-1096.
13. Feinstein, R., B. A. Gooden, and H. R. Skutt. 1973. New techniques for measuring cardiorespiratory responses in free-swimming scuba divers. In: Aerospace Med. Assoc. 1973 Annual Sci. Meeting (Preprints). Las Vegas, Nevada: Aerospace Med. Assoc.
14. Fell, R. B., A. Hudson, and H. R. Skutt. 1972. Two systems for telemetry of physiologic data from ocean divers. 25th Annual ACEMB Meeting, Bal Harbour Fla. (Preprints). Arlington, Va.: Alliance for Engineering in Medicine.
15. Forgays, D. G., G. McClure, and F. C. Evering, Jr. 1973. Modulated light transmission for electrical isolation in a multichannel physiologic monitoring system. Aerospace Med. 44:68-70.
16. Hall, D. A., and A. Slater. 1974. An ultrasound telemetered physiologic data acquisition system. In: Proc. 1st Annual Meeting N. Pacific Branch Undersea Med. Soc. Avalon, Calif: Univ. So. Calif.
17. Haugen, D. P., and E. O. Belcher. 1974. Emboli Doppler signal characteristics obtained from the transducer near field region. In: Proc. 1st Annual Meeting N. Pacific Branch Undersea Med. Soc. Avalon, Calif.: Univ. So. Calif.

18. Jarrett, A. S. 1966. Alveolar carbon dioxide tension at increased ambient pressures. J. Appl. Physiol. 21:158-162.
19. Kanivisher, J., K. Lawson, and R. Strauss. 1974. Acoustic telemetry from human divers. Undersea Biomed. Res. 1:99-109.
20. Kinney, J. A. S., C. L. McKay, A. Mensch, and S. M. Luria. 1971. The visual evoked cortical response as a measure of stress in Naval environments: methodology and analysis. (2) Rapid flash rates. U.S. Nav. Submar. Med. Cent. Rept. NSMRL 681.
21. Komarov, R. I., I. A. Sapon, S. D. Polojencev, and U. F. Tarasuk. 1974. Problemy biologicheskoi telemetrii pod vodoi. Voennomed Zh. (8):66-70.
22. Lupal, V. V., and A. I. Selivra. 1968. Registration technique of oxygen tension in the brain and the myocard with simultaneous recording of EEG and ECG. In: Giperbariyevaya epilepsiya i narkoz. Neyrofiziologicheskiye issledovaniya. Leningrad: Isadtol'stvo Nauka.
23. MacInnis, J. B., L. A. Trovato, R. W. Hamilton, and H. R. Schreiner. 1966. Biological effects of helium on man: Results of a multi-day exposure to this gas at 20 atmospheres. Aerospace Med. 37:289.
24. MacKay, R. S. 1973. Ultrasonics and the diver. Oceans 2000. 3rd World Congr. Underwater Activities. London: Brit. Sub-Aqua Club.
25. Maitland, G., and J. R. Thomas. 1974. Frequency spectrum analysis of speech changes during open sea habitat and hyperbaric chamber dives. Aerospace Med. 45:855-859.
26. Mans, Y., and I. Nashimoto. 1972. Diving data recorder. Proc. 1st Joint Meeting U.S.-Japan Panel Diving Technology (U.S.-Japan Conf. on Natural Resources Development). Tokyo: Ministry of Agriculture and Forestry.
27. Martin, K. J. 1973. Current research into the normal dive. In: Blood-Bubble Interaction in Decompression Sickness, edited by K. N. Ackles. Ontario, Canada: Defense and Civil Inst. of Environmental Medicine.
28. Monitoring the deep diver. 1969. New Science 41:347.
29. Moritz, W. E., P. A. Van Akkeren, and R. G. Buckles. 1972. A computer based physiologic monitoring system. U.S. Nav. Med. Res. Inst. Rept. 1.
30. Moritz, W. E., and P. A. Van Akkeren. 1972. A 15 channel multiplexed analog data transmission system. U.S. Nav. Med. Res. Inst. Rept. 1.
31. Moritz, W. E. 1971. Physiologic monitoring in hyperbaric environments. In: Abstracts of BuMed-ONR Sponsored Navywide Research in High Pressure Biomedicine Res. Groton, Conn.: Nav. Submar. Med. Res. Laboratories.
32. Moritz, W. E. 1973. A system for studying the physiologic response of divers to hyperbaric environment. Ocean 73. 1973 IEEE Intern. Conf. Engineering Ocean Environment. IEEE Publication 73-CHO-7740-OCC.
33. Morlock, J. F., and R. H. Dressendorfer. 1974. Modification of the Quinton-Monark bicycle ergometer for underwater use. In: Proc. 1st Annual Meeting Undersea Med. Soc. Avalon, Calif.: Univ. So. Calif.

34. Ohuchi, T., S. Meyer, and T. Teraura. 1972. Catheter-mounted oxygen electrode for monitoring oxygen tension. Cardiovascular Res. Cent. Bull. 10:111-122.

35. Pilmanis, A. A., R. D. Rader, J. K. C. Menriksen, and J. P. Meehan. 1974. Instrumentation for underwater data acquisition. In: Proc. 1st Annual Meeting N. Pacific Branch Undersea Med. Soc. Avalon, Calif.: Univ. So. Calif.

36. Ponomarev, V. P. 1973. A self-evaluation test--a functional test for selection and monitoring of training in underwater swimmers. Sportsmen-Podvodnik 35:27-33.

37. Powell, M. R. 1974. Doppler ultrasound monitoring of venous gas bubbles in pigs following decompression with air, helium, or neon. Aerospace Med. 45:505-508.

38. Powell, M. R. 1971. Mechanism and detection of decompression sickness. Tech. Memo. UCRI-673. Tarrytown, N.Y.: Ocean Systems, Inc.

39. Rubissow, G. V., and R. S. Mackay. 1974. Decompression study and control using ultrasonics. Aerospace Med. 45:473-478.

40. Sem-Jacobsen, C. W., and O. B. Styri. 1972. ECG arrhythmias monitored from free swimming scuba divers at various depths. In: 3rd Intern. Conf. Hyperbaric Underwater Physiol., edited by X. Fructus. Paris: Doin.

41. Shaw, R. F. 1972. New non-invasive continuous blood oxygen monitoring using eight waveband photometry. Circulation 48 (Suppl. 4): IV-13.

42. Shurubura, A. A. 1974. Dinamika razvitiya gazovyk puzyr 'kou, vyzvannuyh dekompressiei. Dokl. Akad. Nauk SSR 214:1228-1231.

43. Slater, A., S. Bellet, and D. G. Kilpatrick. 1969. Instrumentation for telemetering the electrocardiogram from SCUBA divers. I.E.E.E. Trans. Biomed. Eng. 16:148-151.

44. Slater, A., and S. Bellet. 1969. An underwater temperature telemetry system. Med. Biol. Eng. 7:633-639.

45. Spencer, M. P., D. C. Johnson, S. D. Campbell, and W. F. Postles. 1974. Clinical use of blood bubble detection in diagnosis, prevention, and treatment of decompression sickness. In: 5th Intern. Hyperbaric Congr. Proc., edited by W. G. Trapp, E. W. Barmister, A. J. Davison, and P. A. Trapp. Burnaby, Canada: Simon Fraser Univ.

46. Spencer, M. P., and H. F. Clarke. 1972. Precordial monitoring of pulmonary gas embolism and decompression bubbles. Aerospace Med. 43:762-767.

47. Spencer, M. P., N. Simmons, and H. P. Clarke. 1971. A precordial transcutaneous cardiac output and aeroembolism monitor. Fed. Proc. 30:703.

48. Tresausky, G. J. 1973. The NMRI Mark III Mod I tremor device. U.S. Nav. Med. Res. Inst. Rept. 2.

49. Tucker, D. G., and V. G. Wesley. 1968. Ultrasonic monitoring of decompression. Lancet 1;1253.

50. Ultrasonic Doppler flowmeter monitors bloodstream bubbles. 1968. Undersea Technol. 9:34.

51. Unsworth, I. P., J. Williams, and R. Taylor. 1969. A simple technique of underwater hardwire. ECG recording. Biomed. Eng. 4:74-76.

52. Utjamishev, R. I. 1974. Medical engineering for hyperbaric oxygenation. In: 5th Intern. Hyperbaric Congr. Proc., edited by W. G. Trapp, E. W. Bannister, A. J. Davison, and P. A. Trapp. Burnaby, Canada: Simon Fraser Univ.

53. Walder, D. N., A. Evans, and H. V. Hempleman. 1968. Ultrasonic monitoring of decompression. Lancet 1:897-898.

54. Weltman, G., and G. H. Egstrom. 1968. Underwater heart rate telemetry using an ultrasonic voice communication system. Aerospace Med. 39:1354-1355.

55. Zierdt, C. H., and E. L. Sharp. 1974. A physiological monitoring system for divers to 1500 feet. In: The Working Diver-1974, Symp. Proc. Washington, D.C.: Marine Tech. Soc.

56. Zweizig, J. R., W. R. Adey, J. Hanley, P. M. Hahn, A. A. Pilmanis, R. R. Civen, and A. T. K. Cockett. 1972. EEG monitoring of a free-swimming diver at a working depth of 15 meters. Aerospace Med. 43:403-407.

MEDICAL AND PARAMEDICAL

(Retitled - Selection and Training of Physicians and Paramedics for Offshore Diving

Part #5T of the

National Plan for the Safety and Health of Divers in their Quest for Subsea Energy

Produced by:

Eric P. Kindwall, M.D. (Chairman)
Director, Dept. of Hyperbaric Medicine
St. Lukes Hospital, Milwaukee, Wisconsin

Harold M. Ginzburg, M.D.
Medical Director, Tarrytown Labs, Ltd.

Chester Langworthy, HMC (DV 1) USN, Ret.
Marine Equipment Specialist, NMRI

Joseph E. Rood, Jr., EMT-Paramedic
Training Officer, Emergency Medical Services Project
Medical College of Wisconsin

David A. Youngblood, M.D.
Medical Director, Oceaneering International, Inc.

TABLE OF CONTENTS and Organization for part 5T

MEDICAL AND PARAMEDICAL
(Selection and Training of Physicians and Paramedics for Offshore Diving)

I. The Demand

II. Available Personnel

- A. Medical
- B. Paramedical

III. Education and Training Facilities

- A. Medical
- B. Paramedical

IV. Recommendations

- A. Physician
  1. Categorization
  2. Recruitment and Selection
  3. Training
  4. Training sites
  5. Implementation
  6. Course and Examination Preparation
  7. Awarding of Diplomas
  8. Priorities
- B. Diver Life-Support Specialists
  1. Recruitment
  2. Selection
  3. Training
  4. Deployment
  5. Course Curriculum and Competence Requirements
  6. Certification
  7. Priorities
  8. Implementation

Selection and Training of Physicians and Paramedics for Offshore Diving

I. The Demand

Historically, diving companies as well as tunneling firms have made little or no use of physicians. But, as diving became more complex and our knowledge of the diagnosis and treatment of diving disorders became more sophisticated it was recognized that medical personnel were needed. However, diving companies had little or no experience in relating to a physician, understanding his role, or judging his competence. With the advent of extremely deep diving and saturation techniques, these historical difficulties mushroomed almost overnight into a problem of immense proportion.

It has become abundantly clear to everyone concerned that medical backup and/or supervision is mandatory for certain operations, and the companies dealing with men working under pressure have been forced to seek immediate medical backup. Complicating the situation is the fact that the speciality of diving medicine and the treatment of pressure-related diving accidents is an extremely narrow field, and there are relatively few qualified physicians available. Finding and retaining a physician of known competence in this area is a must for those companies carrying out complex diving or saturation procedures, but there are as yet no mechanisms which allow diving companies to gauge the diving or hyperbaric medical competence of any physician selected.

II. Available Personnel

A. Medical

There are a few retired Navy medical officers who have had training in both diving and submarine medicine but there are not enough to meet the major need for medical care for the diving community. As a matter of fact, it is very doubtful if it would be possible to get many physicians who would be willing to spend their time on a rig or platform. Instead, they should be in a hospital or nearby clinic where they could be contacted by radio or telephone.

There are a fair number of physicians who have had the 8-day training courses given at Hawaii and in the Bahamas. But this group does not have enough experience to be qualified to handle the multitude of problems arising in present day diving activity.

There is definite need for a trained cadre of physicians to act as backup for the paramedicals actually on the rigs or platforms.

B. Paramedical

The Navy also provides a small number of diving pharmacist's mates who would qualify as Diver Life-Support Specialists, but once again they are too few in number to meet today's need.

There are, of course, emergency medical technicians of varying degrees of training who could handle certain types of emergencies, but they have no knowledge of diving and the various aspects of compression and decompression, so they are only minimally trained for the required task. Once again, the need is great and a training program must be instituted to handle the problem.

III. Education and Training Facilities

A. Medical

The Navy has training facilities but they are not available to the civilian community. The Air Force has a training program for physicians at Brooks Air Force Base Hospital, and they have agreed that it is possible for this training to be made available to physicians. Eight-day courses are given at the University of Hawaii and at Freeport in the Bahamas, and a recent course is being given at the University of Southern California. However, there is no training for medical personnel in the United States that gives any kind of degree. Such training is available at Balmoral in Australia. There is a need for readily available training facilities for in-depth training of a selected group of medical personnel. There is also a real need for at least some knowledge of diving and hyperbaric problems to be given as part of the training of every physician. The mismanagement of treatment by untrained doctors has been deplorable.

B. Paramedical

There are a number of facilities for the training of what are variously called paramedical, emergency medical technicians, and doctors' assistants. However, there are no schools at the present time in the United States where an individual can be trained for emergency underwater medical problems. Several courses are in the planning stage and these should very definitely be encouraged and assisted in every way possible.

IV. Recommendations

A. Physician

1. Categorization

To provide diving companies with information about the competence of any given physician in regard to pressure-related diving accidents and/or physical examination of divers and the treatment of diving casualties, the committee recommends that physicians licensed in any state or country be categorized as follows:

Category I-A.

Physicians who: have had at least two months' training in the hyperbaric treatment of decompression sickness or gas embolism as well as non-diving diseases; have passed an examination required by an appropriate certifying medical organization; are familiar with saturation diving procedures; and have successfully supervised treatment of at least five cases of decompression sickness and/or gas embolism.

Category I-B.

Physicians who: have had at least two months' training in the hyperbaric treatment of decompression sickness or gas embolism as well as non-diving diseases; have passed an examination required by an appropriate certifying medical organization; are familiar with saturation diving procedures; and have successfully supervised treatment of less than five cases of decompression sickness and/or gas embolism.

Category II-A.

Physicians who: have completed established military diving medical training programs of at least four weeks' duration; have passed an examination required by an appropriate certifying medical organization; are familiar with saturation diving procedures; and have successfully supervised treatment of at least five cases of decompression sickness and/or gas embolism.

Category II-B.

Physicians who: have completed established military diving medical training programs of at least four weeks' duration; have passed an examination required by an appropriate certifying medical organization; are familiar with saturation diving procedures; and have supervised treatment of less than five cases of decompression sickness and/or gas embolism.

Category III.

Physicians who have taken a five-to-eight-day course in diving medicine sponsored or cosponsored by the Undersea Medical Society or have taken the five-day course given at the Royal Naval Physiologic Laboratory at Alverstoke, Gosport, Hants, England

Category IV.

Physicians who have had a two-day orientation course in diving medicine, sponsored or cosponsored by the Undersea Medical Society.

2. Recruitment and Selection

The committee contacted the American College of Emergency

Physicians and spoke with President William P. Haeck. The American College of Emergency Physicians is willing to cooperate in any way to establish a program to upgrade physician training in diving medicine.

The committee recommends that an appropriate medical group be formed to assist the American College of Emergency Physicians in selecting speakers for the ACEP state chapter meetings in key areas. In practical terms, key areas are those states bordering the coasts where offshore operations are now in progress or may soon be in progress. Following lectures in these areas, an article should be prepared for publication in the Journal of the American College of Emergency Physicians describing the medical problems of diving and the courses available to the would-be diving physician.

3. Training

The committee recognizes that a formal, in-depth course is necessary for the training of physicians in Category I. To date, the only such course in the world readily available to civilian physicians is that held at the School of Underwater Medicine, H.M.A.S. Penguin, Balmoral, N.S.W., Australia; this course leads to a Diploma of Diving and Hyperbaric Medicine. A course leading to an identical diploma should be developed in this hemisphere.

Such a course would include training in nondiving as well as diving-related uses of the hyperbaric chamber, and should be taught, at least in part, at a university facility. An additional requirement would be that a chamber facility be available and that a portion of the faculty be experienced in hyperbaric medicine (nondiving) as well as diving medicine. The course format should be as comprehensive as the present Australian course, and should be up-dated yearly.

4. Training Sites

It is probable that no one training site will have all of the facilities and expertise for the proposed training. For example, not all centers where hyperbaric (nondiving) experience or diving experience is available, have facilities for saturation training.

Among sites which do presently have this capability are;

1) Brooks Air Force Base, School of Aerospace Medicine,
   San Antonio, Texas

2) Defense and Civil Institute of Environmental Medicine,
   Downsview, Ontario, Canada

3) Duke University Medical Center, F. G. Hall, Laboratory for Environmental Medicine, Durham, North Carolina

4) University of Pennsylvania, Institute for Environmental Medicine, Philadelphia, Pennsylvania

5) Medical College of Wisconsin, Dept. of Environmental Medicine, Milwaukee, Wisconsin

5. Implementation

All these recommendations should be implemented as soon as the necessary examinations and course outlines are completed and the necessary funds are available.

6. Course and Examination Preparation

An appropriate group should develop the requisite course outlines, write, administer and grade the examinations. This same group should also coordinate the courses at participating institutions.

7. Awarding of Diplomas

Diplomas in Hyperbaric and Diving Medicine should be issued by the appropriate certifying medical organization.

8. Priorities

1) The workshop to develop the 2-day diving medicine orientation course should be held as soon as possible.

2) Teaching institutions named in this document should be contacted to determine the extent of their ability to participate.

3) A course outline for preparing Category I physicians should be developed by May 1976.

B. Diver Life-Support Specialists

a. Recruitment

The committee recommends recruitment among ADC qualified divers or systems divers with a minimum of 100 field days diving or tending.

b. Selection

The committee recommends that selection be limited to volunteers who meet the following requirements:

1) Minimum age--21

2) High School education or equivalent

The committee also recommends that preferential consideration be given in the following order:

3) Medical experience

a) Qualified candidates who are veterans with military experience such as U.S.N. Independent Duty Hospital Corpsmen, U.S. Army Special Forces Medics, or U.S.A.F. Paramedics

b) Qualified candidates with other previous medical or paramedical experience

4) Educational background

a) Qualified candidates with college credits

C. Training

The committee recognizes that the hazardous, isolated, and specialized nature of diving operations requires a high level of emergency medical competence. In addition to their usual duties, Diver Life-Support Specialists should be able to provide emergency care and treatment of diving accidents plus immediate care and treatment to any injured or acutely ill personnel on the job.

1) Medical Duties and Responsibilities

Diver Life-Support Specialists may do the following:

a) Render emergency care, rescue and resuscitation services

b) Administer parenteral medications under the direct supervision of a physician or a registered nurse during training at a hospital, ambulance, or other medical facility and while caring for patients in such hospital or facility.

c) Perform cardiopulmonary resuscitation in a pulseless, nonbreathing patient.

d) Where voice contact or a telemetered electrocardiogram is monitored by a physician and direct communication is maintained, Diver Life-Support Specialists may upon order of such physician do any of the following:

(1) Administer intravenous solutions

(2) Perform gastric or tracheal suction or intubation

(3) Administer parenteral injection of any of the following classes of drugs:

(a) antiarrhythmic

(b) vagolytic agents

(c) chronotropic agents

(d) analgesic agents

(e) alkalinizing agents

(f) vasopressor agents

(g) anticonvulsive agents

(h) other drugs which may be deemed necessary by the ordering physician

(4) Perform cardiac defibrillation

4. Deployment

It is particularly important to carefully consider the matter of the position of the Diver Life-Support Specialist. Such questions as the following should be carefully weighed in setting up the 'medical' organization:

1) How many men should be allowed on a diving rig before a Diver Life Support Specialist is required?

2) What authority does he have in handling injured men or in ordering transportation ashore?

3) What are his diving duties as a member of the diving team?

This, of course, logically points out the need for careful consideration of expert medical assistance being available by phone or radio.

5. Course Curriculum and Competence Requirements

Diver Life-Support Specialists should be competent in the specific theory, practice, and manipulative skills which an appropriate agency on Selection and Training of Diver Life-Support Specialists determines and requires.

6. Certification

Diver Life-Support Specialists should be certified by an appropriate agency or medical organization. They should be certified initially upon successful completion of an approved training program for a provisional period of 1 year, and thereafter annually, following a minimum 10-day refresher program at an approved facility.

7. Priorities

1) A workshop on the Selection and Training of Diver Life-Support Specialists should be held as soon as funds become available.

2) An appropriate agency or medical organization should be chosen to act as a certifying body.

3) Funding necessary for carrying out the above outlined training programs should be sought from the appropriate agencies or organizations.

8. Implementation

Upon completion of the above priorities, the chosen certifying body should contact the appropriate participating institutions and coordinate the immediate implementation of the training programs.

LEGAL AND COMPENSATORY ASPECTS

Part #6T of the

National Plan for the Safety and
Health of Divers in their Quest
for Subsea Energy

Produced by:

Peter B. Bennett, Ph.D. (Chairman)
Co-Director, F. G. Hall Environmental
Research Laboratory
Duke University Medical Center
Durham, North Carolina

L. J. Christoffersen
Safety Director, Taylor Diving and
Salvage Company, Inc.
Belle Chasse, Louisiana

H. Ray Curtis
Manager, Ocean Systems, Inc.
Morgan City, Louisiana

James Dawson
Managing Director, Undersea Projects
Insurance Brokers, Ltd.
London, England

John Harter, P.E.
President, Harter Underwater Corporation
Edgewater, Maryland

Harold Lamy, Attorney
New Orleans, Louisiana

Nolan Prejeant
Highland Insurance Company
New Orleans, Louisiana

Stanley Rauhut, Attorney
Houston, Texas

Paul Woodhall
President, Professional Divers Local #1012
United Brotherhood of Carpenters and Joiners
Gretna, Louisiana

TABLE OF CONTENTS and Organization for part 6T

Legal and Compensatory Aspects

I. LEGAL ASPECTS 1

- A. Legal Recoveries of Divers Injured or Killed While Covered by United States Law
- B. Safety Laws Affecting the Industry
- C. Legal Liability of Medics and Paramedics

II. INSURANCE ASPECTS 8

- A. Problems

III. RECOMMENDATIONS 8

- A. National Safety and Health Standards for Diving
- B. Legal and Compensatory Recommendations
- C. Different Opinions on Legislative Changes

This report will not be concerned with international law or conflicts of law. Instead, it will concentrate on the complex question of legal and insurance coverage for divers and others involved in offshore diving. The committee will also propose some changes in the present legal and compensatory situation which would benefit the diving industry as a whole.

I. LEGAL ASPECTS

The legal recoveries of divers who are citizens of the United States but who are injured while working for non-U.S. owned companies in foreign waters may well be governed by foreign law. On the other hand, U.S. law may govern U.S. citizens who are working as divers for U.S. owned companies in foreign or international waters. Contractual elections do not usually determine the applicable law.

A. Legal Recoveries of Divers Injured or Killed While Covered by United States Law

What law determines the benefits recoverable by a diver or his heirs under U.S. law depends in large measure upon the diver's status at the time of the accident. The term status involves such considerations as: 1) whether the diver is a seaman or non-seaman; 2) the locality of the work station, and 3) the situs of the accident.

Certain statutory and general laws are applicable:

1) The Merchant Marine Act of 1920, commonly known as the Jones Act, 46 U.S.C. 688, which provides for a negligence action by a seaman against his employer;

2) The Longshoreman and Harbor Workers Compensation Act (LHWCA), 33 U.S.C.-A., 903, which provides statutory weekly compensation benefits and medical and death payments to longshoremen and harbor workers injured on navigable waters and in areas related by statute;

3) The Outer Continental Shelf Lands Act (OCSLA), 43 U.S.C.-A., 1333, which makes the Longshoremen and Harbor Workers Compensation Act applicable to covered accidents occurring more than three miles (one marine league) from the shore of the states. (The latest tideland decision has now made the three-mile limit defineable.)

4) The state Workmen's Compensation statute applicable to the waters within the three-mile limit;

5) The general maritime law of the United States, which includes the "warranty of seaworthiness" owed by a vessel owner to seamen. The warranty of seaworthiness is an absolute, non-delegable duty obliging a vessel owner (including a bare-boat charterer) to supply members of the crew with a reasonably safe and seaworthy vessel, including its equipment, appurtances, and crew. The

obligation is absolute and not based on fault.*

6) The tort law of the state having jurisdiction of the waters involved or of the situs of the accident, which may include an offshore platform where adjacent state law applies under OCSLA pursuant to the U.S. Supreme Court decision in Rodrigue v. Aetna Casualty and Surety Co., 1969, 395 U.S. 352, 89 S. Ct. 1835, 23 L. Ed. 2d 360, 1969 AMC 1082;

7) The "maintenance and cure" recovery by a seaman against his employer. This right of recovery is a type of compensation which the seaman has in addition to, and which is not contingent on, a Jones Act or general maritime law recovery. The maintenance recovery is the seaman "found" or an allowance to provide accommodations of board and lodging consistent with that aboard his vessel. (The union collective bargaining rate under present contracts is $8.00 per day). In addition to maintenance, the seaman has a right to medical treatment; the maintenance remedy ceases when the seaman reaches "maximum medical cure." The maintenance and cure remedy is applicable to any malady, illness, or injury that manifests itself during the employment. The malady or illness need not be caused by the seaman's employment to be compensable; it must merely become symptomatic during the employment.

In death cases, additional statutes and general laws may be applicable:

1) The Death on the High Seas Act, DOSA, 46 USCA 761, which provides for a wrongful death recovery to certain survivors where death occurs beyond the three-mile limit;

2) The state wrongful death and survival statute applicable to the waters involved or the situs of the accident (see 5) above).

3) The general maritime law death recovery embodied in the U.S. Supreme Court decisions of Moragne v. State Marine Lines, 1970, 398 U.S. 375, 90 S. Ct. 1772 and Sea Land Services Inc. v. Gaudet, 1974, 4/4 U.S. 573, 94 S. Ct. 806. It is too early to determine how far reaching these decisions may be, but they may be extended to all maritime deaths, wherever they occur.

1. Divers as Seamen Under the Jones Act

The term seaman is synonomous with "member of the crew of a vessel." If a diver is a member of the crew of a vessel, he is a seaman, and is consequently covered by the laws applicable to seamen, i.e., the Jones Act and the general maritime law warranty of seaworthiness. The criterion for determining who is a member of the crew of a vessel is set out rather clearly in the U.S. Fifth Circuit decision in Offshore v. Robinson, 266 F 2d, 5th Cir. (1959).

---

*See Mitchell v. Trawler Racer, Inc., 262 U.S. 539, 80 S. Ct. 926 (1960), A.M.C. 1503 (1960).

Generally, if the worker has a more or less significant attachment to a vessel or group of vessels, and his duties play a part in carrying out the function or mission of the vessel, he is a seaman. Clearly, a diver who is quartered on a drilling or derrick barge or work boat, and who is assisting the vessel to carry out its mission, is a member of its crew. A diver need not be involved in the navigation of the vessel, i.e., he need not "hand reef or steer", to be a member of its crew. Under this line of decisional law, musicians and beauticians aboard oceanliners have been accorded "seamen" status.

In the United States District Courts of Louisiana, where much litigation involving divers is being conducted, divers have been held to be seamen as a matter of law. Presiding judges of the trial court have granted a summary judgment on "seaman status" for divers who have filed a personal injury suit against their employers under the Jones Act and general maritime law.*

The Jones Act provides an unrestricted recovery action for provable special and general damages. To recover, the seaman or his heirs must prove negligence, however slight, on the part of the employer, or some "unseaworthiness" on the part of the vessel, its appurtances, or crew. Without this proof, the seaman's recovery would be limited to maintenance and cure benefits.

It has been held that a seaman need not be injured on the vessel to recover under the Jones Act. District court decisions have held that divers who are injured on the sea bottom, in bells, or while undergoing decompression may have a potential Jones Act remedy. The elements of recovery under the Jones Act and general maritime law include the following:

1) Pain and suffering
2) Loss of wages to date of trial
3) Future loss of wages discounted over the work-life of the worker
4) Medical expenses, past and future
5) Disability and disfigurement, including loss of enjoyment of life

---

*For example, see John Alvenis v. J. Ray McDermott and Travelers Insurance, No. 73-1220, U.S. District Court, Eastern District of Louisiana, New Orleans, La.

In death cases, the survivors may recover for the following:

1) Loss of support, discounted over the decedent's work life

2) Loss of services of decedent

3) Loss of society, i.e., companionship, consortium, love and affection

4) Loss of nurture to the minor children, namely the guidance, and counsel of the deceased father to his children during their minority

5) Funeral expenses

2. Divers Under Workmen's Compensation Acts

If the diver is not a member of the crew of a vessel, his legal remedies against his employer are governed by the applicable federal or state workmen's compensation statute.

a. Federal Longshoremen and Harbor Workers Compensation Act

The LHWCA expressly excludes members of the crew from coverage, and is applicable beyond the three-mile limit to the exclusion of any state compensation statute. Thus, a diver injured on an outer continental shelf platform (which the courts have held not to be a vessel) or while diving from such a platform will presumably be covered by the LHWCA.

Within the three-mile limit, the areas of legal jurisdiction are somewhat unsettled. The water line is no longer the demarcation point between State and Federal jurisdiction. The 1972 amendments to the LHWCA make it applicable "to an injury occurring upon the navigable waters of the United States (including any adjoining pier, wharf, dry dock, terminal, building way, marine railway, or other adjoining area customarily used by an employer in loading, unloading, repairing or building a vessel.)" Many of the potential jurisdictional complications remain to be ironed out, e.g., if a diver were assisting in repairing a vessel, but diving from a pier or inshore platform located within the three-mile limit, would his injuries be covered by the Federal Act?

The benefits of the LHWCA were substantially increased in the 1972 amendments. As of October 1, 1975, the weekly compensation benefits under LHWCA are two-thirds of the injured employee's average weekly wage, but in no event more than 200% of the national average weekly wage. This amount translates to a maximum rate of approximately $330 per week. In total disability cases, the benefits are payable for life. In the event of death, weekly benefits are payable to the widow and to children during their minorities. Benefits to the widow are limited to 50% of the decedent's average weekly wage during widowhood, with two years' compensation in one sum payable upon remarriage.

Upon discharge from active medical care, partial disability of a body member is compensated in accordance with a schedule of weekly payments. In non-scheduled cases, benefits are payable in accordance with loss of wage-earning capacity, which is generally restricted to 2/3 of the difference between the pre-injury weekly wage rate, and the post-injury wage rate or capacity.

Medical benefits under the LHWCA are unlimited and extend for life. Reasonable funeral benefits are payable but do not exceed $1000.

b. State Workmen's Compensation Acts

Occasionally, a diver may not be a member of the crew of a vessel, nor be engaged in activities or at locations which provide coverage under the federal LHWCA. In these instances, the diver's remedies are governed by the applicable state's workmen's compensation law. Benefits under the applicable state workmen's compensation statutes are determined by state statute. Many states are raising their workmen's compensation statutes to comply with projected minimum standards. The prevailing maximum weekly benefits in Louisiana are $85 per week, with increases projected for the next several years. Medical benefits under the Louisiana statute are limited to a maximum of $25,000. Funeral benefits are recoverable up to $1000.

B. Safety Laws Affecting the Industry

1. Pre-1970 Regulatory Authority

Prior to the enactment of the Occupational Safety and Health Act of 1970, there were no safety and health standards affecting divers in the navigable waters of the U.S., except for a few equipment and vessel regulations which were primarily enforced by the United States Coast Guard.

The U.S. Coast Guard's regulations and enforcement efforts were principally directed towards equipment associated with diving operations aboard vessels which required U.S. Coast Guard certification. In general, this involved the inspection and certification of pressurized vessels and the permanent piping of the pressure vessels, investigation of deaths and serious injuries, and making recommendations and comments on the cause of the accident or casualty.

a. Pre-1970 Industry Practice

The requirements and requests of insurance underwriters and the safety practices and procedures of individual diving contractors were the source of safety and health standards for the diving industry prior to 1970. Individual diving companies established safety departments and procedures, and used U.S. Navy guidelines and diving manuals devised by the diving industry to ensure safe diving practices.

Insurance companies also required safety inspections by their own safety investigators, expert certification of equipment by the American Boiler Society or similar experts, that manufacturers' recommendations on equipment be followed, and the use of U.S. Navy procedures as guidelines.

2. Occupational Safety and Health Act of 1970

By enacting the Occupational Safety and Health Act (OSHA) of 1970, Congress decreed as national policy that every employer shall provide each employee a work place free from recognized hazards likely to cause death or serious injury, and every employer shall comply with the safety and health standards promulgated by the Secretary of Labor. The Act further provided that the safety requirements of some regulatory agencies remain in effect and be adopted as temporary standards until the Secretary of [illegible]bor reviews and develops additional or substitute standards for a particular industry.

a. OSHA vs. U.S. Coast Guard Jurisdiction Under the Act

At present, there is some confusion about which agency has the jurisdiction to develop and enforce regulations, and inspect and investigate accidents.

The following practices prevail today in diving:

1) No significant new safety and health standards have been formally promulgated since 1970.

2) The U.S. Coast Guard is enforcing the original safety regulations set forth on page 6T-5 above.

3) The U.S. Coast Guard occasionally inspects diving operations to ensure that the operation and equipment are free from recognized hazards.

4) The U.S. Coast Guard investigates deaths and some of the serious injuries reported, as required under the Act.

5) In some areas of the country, the Occupational Safety and Health Administration is also endeavoring to investigate death and serious injuries occurring in diving operations.

C. Legal Liability of Medics and Paramedics

Under certain conditions, the paramedic (Emergency Medical

Technician/Diver) could be held responsible for negligence which resulted in the injury or death of a patient.* Determination of responsibility under applicable legal principles would be left to the jury or judge hearing the case. However, the company, rather than the paramedic, is more likely to be sued; if the suit is successful, the company would pay the judgment under the legal principle of respondeat superior. Although the standards of responsibility may vary, the paramedic may be held as culpable as any worker of the company. Neither the Jones Act nor any present statutory law requires that a paramedic be on board a ship or work station. Determination of the general responsibility for providing adequate medical care to divers on the job is decided by the Courts on a case-by-case basis.

Nevertheless, the use of paramedics could undoubtedly reduce the severity of injuries and save lives, and simultaneously reduce the number and size of claims and the cost of insurance. There are at present few paramedics trained to treat not only trauma, but decompression sickness and other medical diving problems as well. It may be feasible to have a paramedic at each work site; perhaps all divers or a selected number of divers, tenders, or rack-operators should be trained in emergency first aid and resuscitation methods.

If the physician engaged in treating divers is under contract, or if he is a full-time employee of the company, he may be regarded as an employee of the company and would therefore fall under the legal conditions discussed earlier. If the physician is not under contract but is called on for medical advice or treatment, he would probably be considered an independent contractor and not a company employee; a claim for negligence in such a case would be brought against the malpractice insurance of the individual doctor. Malpractice insurance may not cover a physician who goes out to an offshore work site; few qualified physicians are willing to practice at the work site, because their malpractice insurance premiums would increase considerably. A clear solution to this problem is needed, to ensure adequate and prompt medical support for offshore diving. There are at present no Federal guidelines for the legal liability of paramedics and doctors treating offshore diving accidents.

---

*For specific recommendations about selection and training of medics and paramedics, see Reports 5 and 5T. A recent Undersea Medical Society Workshop, "The Emergency Medical Technician/Diver," sponsored by the United Brotherhood of Carpenters and Joiners, contains a detailed discussion of EMT/Divers and is available from UMS.

II. INSURANCE ASPECTS

A. Problems

The complexity and ambiguity of the medical questions raised by diving accidents make the diving industry and its insurers vulnerable to claims made against them; such claims are exceedingly difficult to defend against, especially in the absence of reliable and independent medical evidence. For example, it is often impossible to distinguish, in these claims, among cases of injury, illness, and congenital defects. Present legislation, such as the Jones Act or general maritime law, makes it relatively easy for the plaintiff to perfect a claim against his employer or the vessel on which he worked, because the law places such stringent obligations on the employer or the vessel. The large number of cases won by seamen, including divers, under the provisions of these laws, attest to the accuracy of this opinion.

The large judgments awarded to plaintiffs under these laws are not at present being offset by insurance premiums from the diving industry; this situation has resulted in a small and shrinking insurance market to protect the diving industry. The large salaries which divers command aggravate this condition. The inability to achieve a spread of risk in the diving industry runs counter to the basic tenet of the insurance industry, one which is particularly important in an inflationary period. The results of this dilemma are deleterious to diving contractors, insurers, and of course to divers, all of whom are dependent on an adequate insurance market.

Evidence that it is more and more difficult to purchase diving insurance, and the reason for this shrinkage, is readily available. Recent claims have resulted in enormous judgments, which have in many cases devoured many years of accumulated profit on insurance portfolios. If the present trend continues, it will be impossible for brokers to develop new markets for diving insurance.

The 'long tail' nature of claims, defended years after the event, is another self-defeating feature of diving insurance. The absence of reliable and unbiased medical evidence from divers' medical records and logs makes it nearly impossible to withstand claims alleged to have arisen from diving accidents occurring many years before. This situation has encouraged a number of insurance companies and underwriters to close down their diving insurance portfolios.

III. RECOMMENDATIONS

A. National Safety and Health Standards for Diving

Since 1970, the U.S. Department of Labor has not published formal safety and health standards for the diving industry. In

1972, the American National Standards Institute (ANSI) attempted to develop safety and health standards for Diver Qualification, Diver Equipment Standards, Diving Procedures Standards, and Diver Medical Certification; the project was known as the Z-135 Safety Standards Project. Because of controversy among the members of the various committees, the proposed safety standards of the Z-135 Project were never adopted by ANSI.

There have been additional efforts and reports by various medical and other industry-related groups on the problem of developing safety standards for the diving industry. These efforts include the diving manuals prepared by the Association of Diving Contractors, the National Oceanic and Atmospheric Administration, the U.S. Navy, and the International Association of Professional Divers, which constitute the principal guidelines for current national safety procedures in the diving industry.

For the purpose of promulgating a single set of standards applicable to all diving contractors and divers in the industry, the committee agrees that formal safety standards should be promulgated in accordance with the Occupational Safety and Health Act; they should be uniformly enforced for all diving operations.

As the agency most familiar with marine operations and most involved in the inspection of marine vessels and operations, the committee recommends that the U.S. Coast Guard retain the enforcement authority, with increased responsibilities and guidelines. This would result in uniform and continuous enforcement of the standards by personnel equipped to inspect and understand diving procedures, operations, and equipment. Retention of enforcement jurisdiction by the U.S. Coast Guard would eliminate duplication of safety inspections, since the Coast Guard has other inspection responsibilities in the industry in addition to the OSHA safety standards. This point was emphasized by the members of the committee who were representatives of the diving contractors.

While the committee encourages the promulgation of safety and health standards for the diving industry, it cautions that the standards should not be so rigid that they prevent research and development of new and safer techniques in the field of hyperbaric medicine. In some instances, not enough is known about diving, e.g., to deeper depths, for the standards to be more than minimum guidelines. Diving decompression tables published by the government should perhaps be viewed as recommendations for minimum practice rather than as regulations. Any published standards should be reviewed, at least annually, to incorporate new research and technological findings. Violations of published standards may provide a more rational basis for damage suits than is possible today.

B. Legal and Compensatory Recommendations

There are two ways in which the diving insurance market can improve standards: by decreasing the number of accidents, and by limiting the liability of underwriters, which would promote a more rational climate. The work currently being done in the field of medical certification for divers will undoubtedly lead to a reduction in the volume of claims. However, limiting liability, combined with the effect of inflation and the delay in legal settlements, is a much more difficult problem.

1. Decreasing Accidents

Though the efforts of the legal profession to protect its diving clients are understandable, the uncertainty and instability created by recent and almost limitless judgments demand a fundamental reappraisal. Recent legislation has been adopted in the United Kingdom, where a panel of diving doctors conversant with all aspects of diving sickness and cures has been appointed to examine divers. Similar legislation should be passed in the United States. The act which established this British medical panel was an extension of an existing Act which protected employees up to the three-mile limit. The new law covers all offshore areas under the jurisdiction of the United Kingdom. Medical certification by government-approved diving medical practioners is now mandatory, and records are kept for every diver operating within the country's jurisdiction.*

Whether this system of medical screening would prove as potent in the United States as it has in the United Kingdom is far from clear; the difference in jurisprudence in tort cases in the U.S. might prove a stumbling block. The Diver Medical Certification section of the Association of Diving Contractor's Manual (1974) would be a good starting point for government regulation of Diving Medical Certification.

2. Modifying Legal Remedies

Limiting liability will only occur through a general change in the benefit provisions of the state compensation acts, LHWCA Act, and other acts governing protection of seamen. Proposed legislation which would bring state compensation laws close to LHWCA benefits is presently before Congress. Adoption of this proposal would not necessarily mean that divers would receive less in benefits than they have in the past.

---

*The diving data collected and analyzed by the medical panel may prove as useful for research as it has for insurance and legal purposes. Data from 2,500 divers has been collected over a period of nine years; re-examination of 600 of these cases disclosed that 18% had suffered bends at some time in their diving careers, 12% had varying degrees of deafness, 7% had sustained permanent vestibular damage, and 3% had aseptic bone necrosis.

Changes in legislation may or may not cause an immediate change in rates or an expansion of markets available to the diving industry. Legislation directed towards removing the diver from Jones Act coverage and placing him under the Longshoremen and Harbor Workers Compensation Act should apply to the entire diving industry. The LHWCA Act does not currently apply to divers who are considered as seamen; the law would have to be changed to place the diving industry under this Act. In view of the Congress' tendency to make piecemeal changes in existing compensation laws, the prospects are not good. Providing the diver with coverage under the LHWCA Act would not entirely limit his remedy to the compensation set forth in this Act; the Act also allows an individual to bring a separate action against a vessel owner for ordinary negligence.

C. Different Opinions on Legislative Changes

The committee which composed this report consisted of attornies, representatives of insurance companies, diving contractors, diving unions, and universities.

Changes in the current legal and compensation remedies under U.S. law involve a number of considerations. There is a general consensus that divers or their survivors are entitled to legal compensation for injuries or death resulting from their work. There are, however, differences of opinion as to which remedies will simultaneously compensate the injured diver or his survivors, promote safe working practices, stabilize the availability of adequate insurance markets, encourage efficiency, and keep the field competitive.

In general, the committee's discussions of possible alternatives centered around the insurance representatives' suggestion that the present legal remedies be modified to cover all divers in the industry under a single compensation act, such as the Longshoremen and Harbor Workers Compensation Act. The following is a summary of the opinions of some of the committee members.

1. Opposition to Changing the Legal Remedies

Opposition to changing the present legal remedies available to divers was voiced by the labor representatives at the meeting. Their position was as follows:

a. The Jones Act provisions of warranty of seaworthiness and maintenance and cure remedies for seamen provide fuller and more adequate compensation to divers than the LHWCA for injuries and death caused by accident.

b. Organized labor has historically opposed any intrusion on Jones Act coverage, on the grounds that the Jones Act and other seamen's recoveries provided greater benefits for those workers covered by it.

c. Making negligence expensive in accident cases promotes safety and a resulting decrease in accidents, with a concomitant reduction in insurance rates. Eliminating fault finding and personal responsibility for accidents promotes an indifference to negligence, because accidents will be tolerated on an actuarial experience basis, i.e., there will be so many accidents a year; the average expense, based on our experience, can be computed and built into the operational budget. Statutory standards with penalties and criminal sanctions will also afford some deterrence.

d. The Jones Act recovery provides a lump sum recovery which encourages economic activity. The compensation recovery is in the form of a scheduled weekly benefit which inhibits the accumulation of sufficient sums for economic mobility.

Finally, the labor representatives emphasized that the legal situation in diving is complicated by the problem of occupational disabilities which may result from physiological changes that divers undergo as a result of diving. Such occupational disabilities deserve special consideration, because they do not lend themselves to legal redress based on fault finding, nor are they usually the result of a single accident which can be isolated and avoided in the future. Medical authorities are not at present in agreement about the etiology of the occupational diseases of divers. Further study should clarify this situation. Detection of one or more of these physiological changes might dictate that the diver cease or restrict his diving, in the interest of his health and the company's liability. The labor representatives believe careful consideration should be given to the question of whether occupational diseases of divers should be compensated under a workmen's compensation scheme, or whether divers would be better covered under adequate disability provisions of private insurance contracts or self-insurance provided by the contractor-employer as a part of the diver's work benefits.

2. Proposals for Changing the Legal Remedies

Representatives of the diving contractors and insurance companies were generally in favor of changing the legal remedies. Their positions are summarized as follows:

a. The purpose of legal changes is not to prevent the divers from receiving compensation when injured or killed; the benefits proposed are the generous weekly benefits already provided under the LHWCA Act in certain diving cases.

b. The recent large judgments and uncertainties of processing claims under the Jones Act has created a need to stabilize the claims process, predict possible recovery limits, and clearly define the acts under which divers can recover in the event of an accident.

c. The laws should be changed to provide a single law under which any diver can recover.

d. There is a need for a medical screening procedure and a permanent medical history record to detect the physiological problems of divers before there is an accident.

e. The present legal situation has resulted in a shrinking insurance market for diving companies. This has resulted in the inability of some diving companies to purchase insurance, especially small diving contractors, and has led to reduced competition in the industry. It also increases the likelihood that small companies will operate without adequate insurance coverage.

f. Changing the law so that all divers are covered by the LHWCA will simplify claim procedures, and reduce the number of law suits, time lost in trial, and the amount of legal expense.

APPENDIX I

Proposal to

National Institute for Occupational Safety and Health

from

Undersea Medical Society, Inc.
9650 Rockville Pike, Bethesda, Md. 20014

in response to

RFP - No. CDC-99-OSH-165(5)

for the preparation of a

NATIONAL PLAN FOR THE SAFETY AND HEALTH OF DIVERS IN THEIR QUEST FOR SUBSEA ENERGY

3 June 1975

Technical Proposal
(Copy)

C W Shilling
Charles W. Shilling, M.D.
Principal Investigator
Executive Secretary

Peter B Bennett
Peter B. Bennett, Ph.D.
President, UMS

Thomas E. Berghage
Thomas E. Berghage
Treasurer, UMS

I. PURPOSE

The Undersea Medical Society, Inc. (UMS), together with the Marine Technology Society (MTS), as a subcontractor, proposes to set in motion an organization that, within a period of six months, will prepare and deliver to the contracting agency (NIOSH) a NATIONAL PLAN FOR THE SAFETY AND HEALTH OF DIVERS IN THEIR QUEST FOR SUBSEA ENERGY.

II. NEED FOR THE EFFORT

A. History

Up until about 1960 almost all of the deep diving in the USA was done by the U.S. Navy. More importantly, almost all of the research prior to that time was supported by or accomplished within the Navy.

Shallow water diving is performed largely in connection with pier construction and harbor work. Within the last 15 years diving, as a sport, particularly with the use of SCUBA, has increased dramatically.

But, until recently, there has been little commercial diving or diving of any sort outside of the above three groups.

Now there is a dramatic increase in deep sea diving in quest of oil. And, from what we are told by our industrial members, the present effort is but a beginning. The energy need is great and oil, not under the control of unfriendly nations, must be found.

B. Available Knowledge

In spite of all of the past research and experience there are many problems arising for which answers do not appear to be available.

What is required is a well organized attack to codify the available knowledge in such a way as to be useful to the diving industry and to the Federal Agencies planning research, training and support programs.

In the process of collecting and analyzing what has been reported and what is known by the experts some answers to present problems may be found, and certainly it will be possible to identify gaps in our knowledge and to suggest areas requiring research and development.

The UMS, with assistance from MTS, proposes to accomplish this study and document:

WHAT is being done
WHO is doing the work
WHERE the work is being done
WORK THAT ought to be done
ORGANIZATIONS or LABORATORIES capable of doing it and
ORDER of PRIORITIES

III. PLAN OF OPERATION

A. Staff Preparation

Search the UMS library file for all material relevant to the problem area, using the Termitrex system.

Read all abstracts for relevance.

Pull or obtain hard copy.

Analyse all of the background material and arrange in order according to the important subject areas. For example: for Osteonecrosis, the reference material in the form of informative abstracts would be grouped under the following headings:

Pathogenesis
Epidemiology
Early diagnostic techniques
Therapy
Problems dealing with workers compensation and
  legislation, i.e., medical-legal problems

This analyzed material will be prepared for use by the special working group "Expert-Authors".

B. Expert-Authors

The Expert-Authors (see section on "Special Working Groups") will assemble for a five-day working period and come up with a series of pertinent recommendations to be added to the bibliographic review. Their report (findings) must include the WHAT, WHO, WHERE, WORK THAT ought to be done, ORGANIZATIONS or LABORATORIES and ORDER of PRIORITIES mentioned above.

The experts will be recognized "authors" of each Special Report. The proposed Expert-Authors from whom selection will be made are listed with each special subject area.

C. Manager-Editor

Work with the "expert-authors" for a maximum of five days making sure that they cover all of the necessary points.

Prepare the final report on their assigned problem area.

Be responsible for each special report being printed, ready for distribution.

D. Special Working Groups

A special working group called the "Expert-Authors" will be formed for each of the problem areas outlined in the proposal. Thus, there will be 18 special working groups.

The average size of the working group will be 3 1/2 individuals (fiscal accounting, i.e., 2, 3 or 4 depending upon the subject area), chosen because of their knowledge and competence in the special problem area. Additional consultants may be called in, if needed.

The composition of each working group will depend upon the subject area; e.g., for bone necrosis, at least two individuals would be biomedically oriented; for testing and certification of equipment, two of the three (or four) would be engineering types; for performance and psychological changes, two would be psychologists expert in hyperbaric activity, etc.

Where appropriate, the working group will have at least one operational person representing field activity.

Selections will be made by the UMS and our subcontractor MTS with approval in each instance of the NIOSH contract monitor.

The operation of the working groups will be as follows:

- Not more than five consecutive working days of the two to four individuals, during which time the prepared literature review and analysis will be critiqued, organized and a determination made as to the areas of research being currently investigated and where it is being done. Recommendations will be made as to what work needs to be done, and all work within a given problem area will be rank ordered as to priority for active support. The work must be completed by the end of the 5th day: NO ONE will be allowed to take work with them to be completed later. For this effort to succeed, a monograph must be put out on the average of one everv ten days; thus each working group must complete its problem area before they leave the meeting.

- To assist in this, a managing-editor will be assigned for the five days to each of the working groups. This person will be responsible for making certain that all of the needed information is obtained and that the report is written up ready for printing.

- Secretarial assistance will be assigned to each working group for typing up their material as they go along and for the final report in camera-ready copy.

- Mrs. Margaret Werts, UMS Bibliographer, will be responsible for furnishing to each working group a package of abstracts and/or hard copy, as desired, of the total literature in the field. Anything not already available will be obtained at once.

E. Reports

1. Monograph for each special area

A monograph will be prepared for each area presented in Section IV. DESCRIPTION OF WORK. The monograph will include an identification of the problem, the data considered, a list of priorities in each work area, the research needs uncovered in the search, an outline of needed work, and recommendations for its accomplishment. The monograph will also contain selected informative abstracts. The monographs shall be capable of "standing alone" and be supplied for approval and use whenever during the contract the study of a given subject area is completed.

2. Progress reports

Progress reports will include the current status and activities planned for the next period; fiscal information including the initial rate of expenditures projected; actual expenditures during report period, and a projection to completion date. Bimonthly, within 10 days following the end of the month, twenty (20) copies will be sent to the Project Officer, and (1) copy to the Contracting Officer.

3. Final report

A draft final report consisting of an overall introduction, discussion, conclusions, and recommendations will be issued. Each subject identified under the scope of work will be addressed. Each monograph required in paragraph E. 1. above will be a chapter of the final report. Draft of the final report will be furnished under this contract prior to any publication or dissemination of the information contained therein, to the Project Officer for review and approval. Thirty days shall be allowed for the Project Officer's approval unless a longer period is agreed upon by the Contracting Officer. The Contractor will prepare and submit the report in final form with 30 days following Project Officer's approval.

Upon approval, a final report in publishable form will be issued in 100 copies to the Project Officer.

It is understood that one copy of this report will be furnished to the Contracting Officer and one copy to the Acting Contractor, Office of Technical Publications.

It is further understood that when either the final report or any of the monographs are completed and approved, we will submit a clean black on white single-spaced, typewritten copy plus all photographs and all drawings suitable for reproduction and that this manuscript is the property of the U.S. Government.

IV. DESCRIPTION OF WORK

The following is a description of categories that will be researched in the development of a NATIONAL PLAN FOR THE SAFETY AND HEALTH OF DIVERS IN THEIR QUEST FOR SUBSEA ENERGY.

It must be remembered that in every instance there will be a previous review of the existing literature dealing with each subject area that will be provided to the Working Group and on which, together with their own personal knowledge, they will base their consideration of the subject area.

Notice should be taken that the individuals suggested for each working area HAVE NOT been contacted as to their willingness to serve. However, we are confident that we will be able to get the necessary 3 or 4 out of the rather large number who have been rank ordered by our "Planning Committee". The number 1 and 2 in each case would be the choice for Chairman and the other members of the working group would be picked from the remaining names.

The following are the proposed working areas:

1. Audio/Vestibular Derangements

In considering audio vestibular derangements, the following areas will be investigated:

Etiology
Diagnosis
Mechanisms involved
Relationships to hearing loss
Sequelae
Treatment

2. Osteonecrosis

The following areas will be considered in developing this important subject:

Epidemiology (incidence)
Early Diagnostic Techniques (to include standardization of x-ray interpretation)
Pathogenesis
Sequelae
Treatment

3. Subtle Physiological Changes

The following physiological changes are considered as they are associated with hyperbaric activity:

Cardiovascular changes
Hematological changes (platelets, etc.)
Serum enzymes
Endocrine changes
Hydrostatic pressure, (subtle effects of)
Nutrition

4. Respiratory/Pulmonary Function in Hyperbaric Exposures

Because of its crucial importance, this subject will be considered separately.

5. Psychological Factors Involved in Undersea-Hyperbaric Exposures

The following areas will be considered:

Selection
Training
Personality changes
Small group interaction
Stress

6. Cognitive and Psychomotor Performance

Performance is the ultimate goal for all underwater work. The following areas will be considered as they affect performance:

Temperature (largely cold)
Human engineering (the impact of all types of equipment, either worn or used by the individual)
Hydrostatic effects
Sensory factors
High Pressure Nervous Syndrome
Environmental
Procedural
Human
Equipment

7. Exchange of Inert Gases, Oxygen and Carbon Dioxide

Areas to be considered are:

Bubble formation and resolution
Cellular and extracellular gas movement
Counterdiffusion phenomena

8. Use of Gases Other than Nitrogen and Helium

The factors to be considered are:

Safety
Thermal conductivity
Diffusion characteristics
Density
Availability and costs
Toxicity

9. Physiological and Toxic Effects of Respiratory and Contaminant Gases (Acute and Chronic)

The special topics to be considered, here, are:

Inert gas narcosis
Effects of increased carbon dioxide
Effects of carbon monoxide
Trace contaminants

10. Oxygen

Factors to be considered are:

Physiological effects
Toxic effects

11. Use of Drugs and other Medical Treatment under Hyperbaric Conditions

This is a particularly important area about which very little is known. The following areas are to be considered:

Injuries occurring under pressure
Use of anesthetics while under pressure
Therapeutic use of antibiotics, antihistamines, etc.
The sequalae of normal illnesses
Surgical procedures

12. High Pressure Nervous Syndrome

The areas to be considered are:

Etiology
Symptomatology (including measurement techniques)
Prevention
Selection
Treatment
Sequelae

13. Microbiological Aspects

Following are the areas to be considered:

The effect of the Hyperbaric Environment on the common organisms in their transmission to members of a group in a diving space.

The introduction of Marine Organisms from the water environment into a habitat or bell.
The effect of hyperbaria on host-parasite relationship.
The effect of hydrostatic pressure on micro-organisms.

14. Thermal Problems

Areas to be considered:

Physiological effects
Evaluation of protective equipment
Treatment and re-warming
Respiratory
Prevention
Metabolic effect

Diving Technology and Resources

1. Operating Standards

Areas to be considered:

Selection of diving personnel
Operating techniques
Selection and training
Personnel qualifications
Procedures
Equipment

2. Compression and Decompression Protocols

Areas to be discussed:

Dive requirements, such as short duration, saturation, excursion, etc.
Treatment

3. Systems Design Criteria

To: Research Existing Standards, Diving Equipment, Tools such as:

Diving and support equipment
Shallow surface
Deep surface
Short duration bell system
Saturation bell system
Submersibles

Habitats
Tools
Research facilities

4. Monitoring Techniques

This is to include all types of physiological monitoring on line, (real time) insitu, in all diving system.

5. Medical and Paramedical

Areas to be covered:

Selection and training
Medical coverage
Medical requirements

6. Legal and Compensatory Aspects

Panel should include representatives from:

Federal Government Court of Claims
(1) Representative from A.D.C.
(1) Union representative
Legal profession
Contractor
Labor Department Attorney
Insurance representative from major Workmen's Compensation carrier

V. CAPABILITIES OF THE UMS

The UMS is uniquely qualified to perform the work described in RFP and in this contract proposal. No other organization has the capabilities, the personnel or the background information.

There are 809 members in the Society, 95% of whom have the M.D. and/or the Ph.D. degree and from analysis of research grant records it appears that well over 90% of all senior scientists working on hyperbaric research are members of the Society. The

Society also has a number of active members of the Commercial Community who have almost unlimited practical experience. From past experience one can say with confidence that they are all both anxious and able to help in any project which will further the safety and proficiency of diving.

The Headquarters' Library contains books, journals and reports and single copies of scientific articles, all of which is under control in a Termatrex system which we consider to be the poor man's computer. All together, there are well over 6,500 documents available for searching, using 350 descriptors. The searches in the past have been most productive and highly satisfactory to the requestors. This library will be used to produce the background information from the literature for utilization by each of the working groups.

The Society has recently been given the Navy Experimental Diving Unit library when it moved to Florida. This will shortly be integrated in the present library and will greatly augment the information available.

The Home Office located on the grounds of the headquarters of FASEB has all the reproduction equipment necessary and has an experienced and dedicated staff capable of performing the management aspect of this proposed contract. In addition, the Executive Secretary of the Society and proposed Principal Investigator of this contract has had over 35 years of experience in the field of underwater activity as a Medical Officer in the Navy and, since that time, in the information-processing activity in the hyperbaric field.

VI. CONTRACT AGREEMENT

The UMS is ready to start upon receipt of the contract. It is proposed that the work will be completed within a six-month period following receipt of contract approval.

It is important to note that at the recent meeting of the Executive Committee of the UMS, in anticipation of a possible contract, an overall management committee was established to act as the coordinating body for this contract. It is composed of the following members:

Dr. Peter B. Bennett
Dr. A. J. Bachrach
Dr. J. W. Miller
Dr. L. M. Libber
Dr. C. J. Lambertsen
Dr. R. W. Hamilton

Mrs. Elizabeth M. Wallace, Marine Technology Society
Mr. Hugh "Dan" Wilson, A.D.C./UMS

plus a representative from each of the interested Federal Agencies:

Dr. Alan H. Purdy - National Institute for Occupational Safety and Health (NIOSH)

Dr. Walter H. Weyzen - Energy Research & Development Administration (ERDA)

Dr. Claude Lenfant - National Heart & Lung Institute, NIH

Assigned to each working group will be a "manager-editor" and a secretary.

A report will be prepared which will cover the subject area in such a way as to stand alone, ready for publication and distribution.

The rationale for this approach is that when you combine what has been reported (the literature) with what is being done (the SSIE) and ask scientists and practical experts in the field to study and analyze a given subject field, you have the best possible approach to an appropriate answer.

The work for the most part will be done in space available at the Federation of American Societies for Experimental Biology, and in the UMS home office, both at 9650 Rockville Pike, Bethesda, Maryland 20014.

The Principal Investigator, Dr. C. W. Shilling, has had over 35 years of experience in research, information handling, and administration in the hyperbaric field. He is author or co-author of eight books, over 80 scientific papers, and hundreds of reports.

The regular staff of the home office of the UMS is completely competent to handle the various administrative details.

But the important aspect of this proposal is that among the active members of the UMS are the world's experts in the various subject areas. And they are willing to help make the project a succes.